NEWNES ELECTRICAL POCKET BOOK

NEWNES ELECTRICAL POCKET BOOK

FOURTH EDITION
(Revised to conform with I.E.E. Regs. 11th Ed.)

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SECTIONAL INDEX

FOREWORD

In this, the Fourth Edition of Newnes Electrical Pocket Book, the opportunity has been taken to include new material and to amend the contents, where necessary.

Although existing conditions do not conduce to substantial additions being made to the editorial scope of the Pocket Book, readers who may have suggestions to make for additional items to be included are invited to communicate with the Technical Books Department of George Newnes Limited, Tower House, Southampton Street, Strand, London, W.C.2.

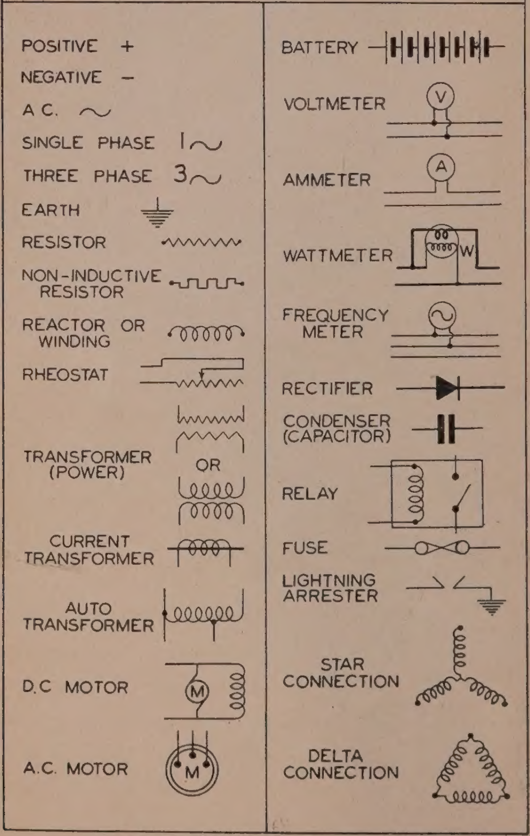
All suggestions will receive careful consideration and it is hoped that by the time the Fifth Edition is called for the prevailing conditions will be such that substantial additions can be made to the facts, figures and other useful data which form the basis of the Pocket Book.

E. M.

CONVERSION TABLE

To Convert:	Multiply by:
Mils to Millimetres (1,000 mils = one inch)	0·0254
Inches to Centimetres	2·540
Centimetres to Inches	0·3937
Feet to Metres	0·3048
Metres to Feet	3·281
Yards to Metres	0·9144
Metres to Yards	1·0936
Miles to Kilometres	1·6093
Kilometres to Miles	0·6214
Square Inches to Square Millimetres	645·15
Square Millimetres to Square Inches	0·00155
Square Yards to Square Metres	0·8361
Square Metres to Square Yards	1·196
Hectares to Acres	2·471
Acres to Hectares	0·4047
Cubic Inches to Cubic Centimetres	16·3
Cubic Centimetres to Cubic Inches	0·0610
Cubic Yards to Cubic Metres	0·7645
Cubic Metres to Cubic Yards	1·308
Pounds (lbs.) to Kilogrammes	0·4536
Kilogrammes to Pounds (lbs.)	2·205
Tons (2,240 lbs.) to Kilogrammes	1,016·02
Kilogrammes to Tons (2,240 lbs.)	0·00098
Ounces (Avoirdupois) to Grammes	28·35
Grammes to Ounces (Avoirdupois)	0·0353
Grains (Troy) to Grammes	0·0648
Grammes to Grains (Troy)	15·432
Gallons to Litres	4·546
Litres to Gallons	0·22
Horse Power to Foot Pounds per Minute	33,000·0
Watts to Foot Pounds per Minute	44·24
Horse Power to Kilowatts	0·746
Kilowatts to Horse Power	1·34
Atmospheres to lbs. per square inch	14·3
Miles per hour to Feet per minute	88·07
Land Miles to Nautical Miles	0·868
Nautical Miles to Land Miles	1·151

GRAPHICAL SYMBOLS



ABRIDGED LIST OF SYMBOLS

A	= cross-sectional area
B	= flux-density
C	= capacitance
D, d	= diameter
E	= electromotive force
f	= frequency in cycles per second
G	= conductance
H	= magnetic force
I, i	= current
L	= inductance
N_1, N_2, etc.	= number of stator and rotor conductors, etc.
n	= revolutions per minute
Q	= quantity of electricity
R	= resistance
r	= radius
s	= slip as fraction of synchronous speed
S_1, S_2	= number of stator and rotor slots
T	= torque
t	= time
V	= voltage, potential difference
W	= watts
X	= reactance
Y	= admittance
Z	= impedance
δ	= air-gap radial length
μ	= permeability
σ	= leakage (dispersion) coefficient
ϕ	= angle of lag or lead
Φ	= magnetic flux (total)
Ω	= ohms
$M\Omega$	= megohms

LIST OF ABBREVIATIONS USED

A.	=	amperes
V.	=	volts
B.H.P.	=	brake horse-power
kV	=	kilovolts
kVA	=	kilovolt-amperes
kW	=	kilowatts
kWh	=	kilowatt-hours
μF	=	microfarads
$\sim$	=	cycles

FUNDAMENTALS

Current.—The term "current" is used to denote the rate at which electricity flows. In the case of a steady flow the current is given by the quantity of electricity which passes a given point in one second. The magnitude of the current depends not only upon the electromotive force but also upon the nature and dimensions of the path through which it circulates.

Ohm's Law.—Ohm's law states that the current in a circuit varies in direct proportion to the pressure and is inversely proportional to the resistance of the circuit. By choosing suitable units this law may be written

$$\text{Current} = \frac{\text{electromotive force}}{\text{resistance}}.$$

The commercial units for these quantities are

Current—the ampere (or amp.) (I)
Electromotive force—the volt (V)
Resistance—the ohm R or (Ω)

Using the symbols I, V and R to represent the above quantities in the order given, Ohm's law can be written

$$I = \frac{V}{R}$$

or

$$V = I \times R.$$

The law not only holds for a complete circuit, but can be applied for any part of a circuit providing care is taken to take the correct values for that part of the circuit.

Specific Resistance.—The specific resistance of any material is the resistance of a piece of material having unit length and unit sectional area. This value is also termed the resistivity. The symbol is ρ. Both centimetre and inch units are used and these can be converted by the following formula:

$$\rho \text{ in inch units} = \frac{1}{2{\cdot}54}\rho \text{ in centimetre units.}$$

The specific resistance of a material is not usually constant but depends on the temperature. The table is given on

page 7 showing the specific resistance of the more usual metals and alloys.

Resistance of a Conductor.—The resistance of a uniform conductor will be given by

$$R = \rho\frac{l}{A}.$$

The units used must be inches and square inches if ρ is in inch units and centimetres and square centimetres if ρ is in centimetre units.

Temperature Coefficient.—The resistance of a conductor at any temperature can be found as follows:

$$R_t = R_o(1 + \alpha t).$$

$$R_t = \text{resistance at temperature } t^\circ \text{ C.}$$
$$R_o = \quad ,, \quad ,, \quad ,, \quad o^\circ \text{ C.}$$

The coefficient α is called the temperature coefficient and it can be described as the ratio of the increase in resistance per degree C. rise in temperature compared with the actual resistance at o° C.

The coefficient for copper may be taken as 0·004, and values for other materials will be found in the table. The increase in resistance for rise of temperature is important, and for many calculations this point *must* be taken into account.

Power.—Power is defined as the rate of doing work. The electrical unit of power is the *watt*, and taking a steady current as with D.C.,

$$1 \text{ watt} = 1 \text{ volt} \times 1 \text{ ampere}$$

or

$$\text{watts} = \text{volts} \times \text{amperes}$$

or

$$W = V \times I.$$

(For alternating current, see section on A.C.)

Note.—1 kilowatt = 1,000 watts.

Energy.—Energy can be defined as power × time, and electrical energy is obtained from

$$\text{Energy} = VIt$$

where t is the time in seconds.

The unit obtained will be in joules, which is equivalent to 1 ampere at 1 volt for 1 second. The practical unit for energy is the kilowatt-hour (Board of Trade Unit) and is given by $\dfrac{\text{watts} \times \text{hours}}{1000} = \text{kWh}.$

TABLE OF SPECIFIC RESISTANCES

Material.	Resistivity. Ohms per Cm.	Conductivity. Ohms per Cm.
Silver	$1 \cdot 66 \times 10^{-6}$	$6 \cdot 03 \times 10^{5}$
Copper	$1 \cdot 78 \times 10^{-6}$	$5 \cdot 62 \times 10^{5}$
Gold	$2 \cdot 42 \times 10^{-6}$	$4 \cdot 14 \times 10^{5}$
Aluminium	$3 \cdot 21 \times 10^{-6}$	$3 \cdot 12 \times 10^{5}$
Tungsten	$5 \cdot 0 \times 10^{-6}$	$2 \cdot 00 \times 10^{5}$
Zinc	$6 \cdot 1 \times 10^{-6}$	$1 \cdot 64 \times 10^{5}$
Brass	$6 \cdot 6 \times 10^{-6}$	$1 \cdot 52 \times 10^{5}$
Platinum	$11 \cdot 0 \times 10^{-6}$	$9 \cdot 10 \times 10^{4}$
Tin	$11 \cdot 3 \times 10^{-6}$	$8 \cdot 85 \times 10^{4}$
Nickel	$11 \cdot 8 \times 10^{-6}$	$8 \cdot 48 \times 10^{4}$
Iron	$13 \cdot 9 \times 10^{-6}$	$7 \cdot 20 \times 10^{4}$
Steel	$19 \cdot 9 \times 10^{-6}$	$5 \cdot 03 \times 10^{4}$
German silver	$16 \cdot 40 \times 10^{-6}$	$6 \cdot 2 - 2 \cdot 5 \times 10^{4}$
Platinoid	$34 \cdot 4 \times 10^{-6}$	$2 \cdot 91 \times 10^{4}$
Manganin	$44 \cdot 0 \times 10$	$2 \cdot 28 \times 10^{4}$
Gas carbon	$0 \cdot 005$	200
Silicon	$0 \cdot 06$	$16 \cdot 7$
Gutta-percha	2×10^{9}	5×10^{-10}
Glass (soda-lime)	5×10^{11}	2×10^{-12}
Ebonite	2×10^{15}	5×10^{-16}
Porcelain	2×10^{15}	5×10^{-16}
Sulphur	4×10^{15}	$2 \cdot 5 \times 10^{-16}$
Mica	9×10^{15}	$1 \cdot 1 \times 10^{-16}$
Paraffin-wax	3×10^{18}	$3 \cdot 3 \times 10^{-19}$

TEMPERATURE COEFFICIENTS

Per Degree C.

Annealed copper	0·00393
Aluminium	0·0039
Brass	0·0016
Iron (wrought)	0·0055
Steel	0·0042
Nickel-chromium 80/20	0·0001

Horse-Power.—1 h.p. = 550 ft.-lb. per second = 33,000 ft.-lb. per minute = 746 watts. From this 1 kilowatt-hour $= \frac{1000}{746} = 1{\cdot}34$ h.p.

Energy Wasted in Resistance.—If we have a current I amperes through resistance R, the volt drop in the resistance will be given by

$$V = IR.$$

The watts used will be VI, therefore the power in the circuit will be $P = VI = (IR) \times I = I^2R$.

This expression (I^2R) is usually known as the copper loss or the I^2R loss.

Heat Equivalent.—The heating value of a current is given by the expression

$$\text{H in B.Th.U.} = \frac{\text{watt-seconds}}{1055}.$$

(One B.Th.U. = heat required to raise 1 lb. of water 1° F.)

Using Centigrade units, the equation becomes

$$1 \text{ C.H.U.} = \frac{\text{watt-seconds}}{1900}.$$

(The C.H.U. is the Centigrade heat unit and is the heat required to raise 1 lb. of water 1° Centigrade.)

C.G.S. Units.—The absolute system of units is based on the **centimetre** as the unit of length, the **gramme** as the unit of mass, and the **second** as the unit of time. The system is therefore often referred to as the C.G.S. system.

In this system **unit force**, producing unit acceleration in unit mass, is called **the dyne.**

Unit amount of **energy** is denoted **the erg,** and is developed by a force of one dyne acting through a distance of one centimetre.

The absolute system of electromagnetic units is based upon **unit magnetic pole.** Two such poles one centimetre apart repel with a force of one dyne.

The absolute unit of current is such that when flowing in a circular loop of one centimetre radius it will exert a force of 2π dynes on unit magnet pole placed at the centre, i.e. a force of one dyne for each centimetre circumference.

The absolute unit of quantity of electricity is represented by unit current flowing for unit time.

Unit difference of potential occurs between two points when the work done in transferring unit quantity from one point to the other is equal to one erg.

COMMERCIAL UNITS

The commercial unit of current, i.e. the ampere, is very closely equal to $\frac{1}{10}$ absolute unit.

The commercial unit of potential difference, i.e. the volt, is 100,000,000, i.e. 10^8 absolute units.

The absolute unit of resistance is such that when unit current flows the potential difference between its ends is unity.

The ohm is practically 10^9 absolute units.

Since it is desirable to have some definite standard of reference, definite standards have now been established to correspond as closely as possible to one ampere $= \frac{1}{10}$ absolute unit and one ohm $= 10^9$ absolute units.

The ampere is therefore defined as the steady current which in one second will deposit silver at the rate of 0·001118 gramme per second when flowing through a solution of silver nitrate in water.

The ohm is defined as the resistance at the temperature of melting ice of a column of mercury 106·300 centimetres long of constant sectional area and weighing 14·4521 grammes.

The volt is determined from the above definitions of the ampere and the ohm ; it is the potential difference that will establish a current of one ampere in a resistance of one ohm.

As a convenient standard of reference, standard cells are used, the E.M.F. of the Cadmium or Weston cell being 1·0183 volts at 20° C.

The Watt.—The power in a circuit is given by the product of *volts* × *amps.* For alternating current circuits this is correct only for instantaneous values.

The Unit.—This is the Board of Trade Unit of Energy (B.o.T.U.) and is the kilowatt-hour (kWh).

ELECTROSTATICS

All bodies are able to take a *charge* of electricity, and this is termed static electricity. The charge on a body is measured by means of the force between the two charges, this force following the inverse square law (i.e. the force is proportional to the product of the charges and inversely proportional to the square of the distance between them). This may be written

$$F = \frac{q_1 q_2}{d^2} \text{ dynes,}$$

where q_1 and q_2 are the charges in absolute electrostatic units and d the distance in centimetres—the space in between the charges being either air or a vacuum.

If the two charged bodies are separated by some other medium the force acting may be different, depending on the *specific inductive capacity* of the *dielectric* between the two charged bodies. The specific inductive capacity is also termed the dielectric constant and the permittivity.

In this case the force is given by

$$F = \frac{q_1 q_2}{\kappa d^2} \text{ dynes,}$$

where κ is the constant for the particular dielectric. For air or a vacuum the value of κ is unity.

Intensity of Field.—There is an electrostatic field due to any charged body and the *intensity* of this field is taken as the force on unit charge. This unit charge is that which, placed 1 cm. away from a similar charge, is acted on by a force of 1 dyne. Like charges repel and unlike charges attract.

The intensity of field at any given point due to an electrostatic charge is given by

$$\epsilon = \frac{q}{\kappa d^2},$$

the charge being assumed as at the centre of the charged body which is assumed to be a sphere.

Dielectric Flux.—The field due to a charge as referred to above is assumed to be due to imaginary *tubes of force* similar to magnetic lines of force, and these tubes are the paths which would be taken by a free unit charge if acted on by the charge of the body concerned.

By means of these tubes of force we get a *dielectric flux-density* of so many tubes of force per square centimetre of area. For our unit we take a sphere 1 cm. radius and give it unit charge of electricity. We then get a dielectric flux-density on the surface of the sphere of unity = one tube of force per square centimetre. The total number of tubes of force will be equal to the surface area of the sphere = 4π. For any charge Q at a distance r the dielectric flux density will be

$$D = \frac{Q}{4\pi r^2}.$$

We have seen that the intensity of field or electric force at any point is

$$\epsilon = \frac{q}{\kappa d^2} = \frac{Q}{\kappa r^2},$$

so that this can also be stated as

$$\epsilon = \frac{4\pi D}{\kappa}.$$

Electrostatic Potential.—The potential to which a body is raised by an electric charge is proportional to the charge and the *capacity* of the body—so that

$$C = \frac{Q}{V},$$

where V is the potential and C the capacity. The definition of the capacity of a body is taken as the charge or quantity of electricity necessary to raise the potential by one electrostatic unit. This unit of potential is the work done in taking unit charge from infinity to a point at unity potential.

Capacitance.—The actual measurement of capacity is termed *capacitance*, and for practical purposes the unit is arranged for use with volts and coulombs. In this case the unit of capacitance is the farad, and we get

$$C \text{ in farads} = \frac{Q}{V},$$

where Q is in coulombs and V in volts. Compared with absolute C.G.S. units 1 farad $= 9 \times 10^{11}$ absolute electrostatic units.

The farad is a rather large unit, so that we usually use the microfarad $= \frac{1}{10^6}$ of a farad, so that 1 microfarad $= 9 \times 10^5$ absolute electrostatic units.

CONDENSERS

The capacity of a body is increased by its proximity to earth or to another body and the combination of the two is termed a condenser. So long as there is a potential difference between the two there is a condenser action which is affected by the dielectric constant of the material in between the two bodies.

Flat Plate Condenser.—Artificial condensers are usually made up of metal plates with paper or other material as a dielectric. The capacity of a plate condenser is found from

$$C = \frac{\kappa A}{4\pi d} \text{ e.s.u.},$$

where A is the area of each plate and d the thickness of the dielectric. Stated in practical units we get

$$C = \frac{\kappa A}{9 \times 10^{11} \times 4\pi d.}$$

For the multi-plate type we must multiply by the number of actual condensers there are in parallel.

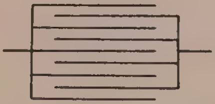
Concentric Condenser.—With electric cables we get what is equivalent to a concentric condenser with the outer conductor or casing of radius r_1 cm. and the inner conductor of radius r_2 cm. If now the dielectric has a constant of κ, the capacity will be (for l cm. length)

$$C = \frac{\kappa l}{2 \log_e \frac{r_1}{r_2}} \text{ absolute electrostatic units}$$

$$= \frac{0{\cdot}039\kappa}{\log_{10} \frac{r_1}{r_2}} \text{ microfarads per mile.}$$

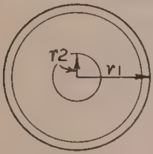
CONDENSERS

PLATE CONDENSER



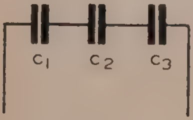
$$C = \frac{\kappa A}{9 \times 10^{11} \times 4\pi d}$$

CONCENTRIC CONDENSER



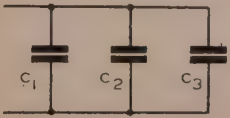
$$C = \frac{0{\cdot}039\kappa}{\log_{10} \frac{r_1}{r_2}}$$

CONDENSERS IN SERIES



$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \cdots}$$

CONDENSERS IN PARALLEL



$$C = C_1 + C_2 + C_3 + \ldots$$

Condensers in Series or Parallel.—Condensers in series or parallel can be said to be opposite to resistance as far as the total resultant capacity is concerned.

Series.—If we have a number of condensers with capacities C_1, C_2, C_3, etc., the resultant capacity in series will be

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \dots}$$

Parallel.—If the condensers are in parallel we get

$$C = C_1 + C_2 + C_3 \dots$$

Values of κ for Different Materials.—The dielectric constant (κ) of an insulating material, often called the specific inductive capacity or permittivity, is the ratio of the capacity of a condenser when using the material as a dielectric to the capacity of the same condenser, having air as the dielectric. The dielectric constant of air is always taken as unity.

The dielectric constants of a few commoner insulators are shown in the following table:

Air	1
Paper, Pressboard	2
Cotton tape (rubbered)	2
Empire cloth	2
Paper (oiled)	2
Shellac	3
Bakelite	6
Paraffin-wax	3
Mica	7
Porcelain	7
Glass	7
Marble	8
Rubber	2·5
Ebonite	2·5
Gutta-percha	4

THE MAGNETIC CIRCUIT

Permanent Magnets.—These are now generally made from cobalt steel. The cobalt content varies from 3 per cent. to 35 per cent. Nickel-aluminium steels are also used and have the advantage that they are lighter in weight than cobalt steels.

Electro-magnets.—Magnetism is supposed to take the form of *lines of force* which flow round the magnetic circuit. This circuit may be a complete path of iron or may consist of an iron path with one or more air-gaps. The transformer is an example of the former and a dynamo the latter.

The lines of force are proportional to the *magneto-motive-force* of the electric circuit and this is given by

$$\text{M.M.F.} = \frac{4\pi \text{IN}}{10}$$

where I is the current in amperes and N the number of turns in the coil or coils. This M.M.F. is similar in many respects to the E.M.F. of an electric circuit and in the place of the resistance we have the *reluctance* which may be termed the resistance of the magnetic circuit to the passage of the lines of force. The reluctance is found from

$$\text{Reluctance} = \text{S} = \frac{l}{a\mu}$$

where l is the length of the magnetic circuit in centimetres, a is the area of cross-section of the magnetic circuit and μ is the *permeability*. The permeability is a property of the actual magnetic circuit and not only varies with the material in the circuit but with the number of lines of force actually induced in the material if that material is iron.

The actual flux induced in any circuit is proportional to the ratio $\dfrac{\text{M.M.F.}}{\text{reluctance}}$ and so we get

$$\text{Total flux} = \Phi = \frac{\text{M.M.F.}}{\text{S}}.$$

The permeability (μ) is always given as the ratio of the number of lines of force induced in a circuit of any material compared with the number of lines induced in air for the same conditions. The permeability of air is taken as unity and so permeability can be taken as the magnetic conductivity compared with air.

Taking the formula for total flux given above, we can combine this by substituting values for M.M.F. and S, giving

$$\text{Total flux} = \Phi = \frac{4\pi \text{IN}.a\mu}{10l}.$$

Having obtained the total flux, we can obtain the *flux density* or number of lines per square centimetre of cross-section as follows:

$$\text{Flux density} = \text{B} = \frac{\Phi}{a}.$$

Where there is an air-gap it will be found that there is a certain amount of magnetic leakage and the actual flux in the air-gap will be smaller than that in the iron. The ratio between these two is given by the leakage coefficient which

$$= \frac{\text{flux in iron}}{\text{flux in air-gap}}.$$

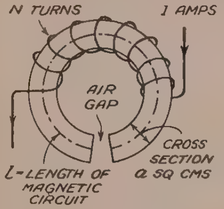
Ampere-turns per Centimetre.—In order to deal with complex magnetic circuits such as dynamos, motors, etc., it is more convenient to take the various sections of the magnetic circuit separately, and for this purpose it is useful to have the ampere-turns required per centimetre to give a fixed flux density. Taking our complete formula above for total flux, we get

$$\text{B} = \frac{\Phi}{a} = \frac{4\pi \text{IN}.}{10l}\mu.$$

so that the permeability and flux density are linked by the expression $\frac{4\pi \text{IN}}{10l}$ which is called the *magnetizing force* and it will be seen that this is equal to $\frac{4\pi}{10}$ (ampere-turns per centimetre) $= 1{\cdot}25$ (ampere-turns per centimetre). The symbol is H.

Now for any given conditions $\mu = \frac{\text{B}}{\text{H}}$, and so $\text{H} = \frac{\text{B}}{\mu}$ or $1{\cdot}25$ (ampere-turns per centimetre) $= \frac{\text{B}}{\mu}$ from which we get ampere-turns per centimetre $= \frac{\text{B}}{1{\cdot}25\mu}$. The relation between B and H is usually given by means of a B–H curve as shown in the diagram, but by using a different scale the actual value of ampere-turn per centimetre required can be read off. This scale is shown in the diagram.

THE MAGNETIC CIRCUIT



$$\text{M.M.F} = \frac{4\pi IN}{10}$$

$$\text{RELUCTANCE} = S = \frac{l}{a\mu}$$

$$\text{TOTAL FLUX} = \Phi = \frac{\text{M.M.F}}{S}$$

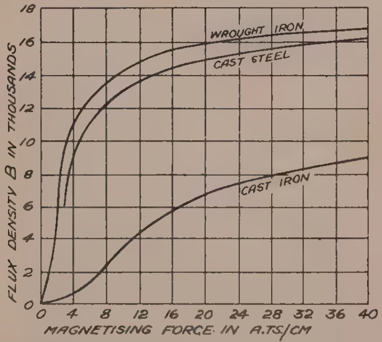
$$= \frac{4\pi IN a\mu}{10 l}$$

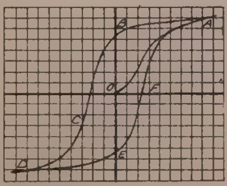
$$\text{MAGNETISING FORCE} = H = \frac{4\pi IN}{10 \cdot l}$$

$= 1{\cdot}25$ (AMP TURNS PER CM.)

$$\text{FLUX DENSITY} = B = \frac{\Phi}{a}$$

$$\text{PERMEABILITY} = \mu = \frac{B}{H}$$





ABCDEF = HYSTERESIS LOOP

OB = REMAINANCE

HYSTERESIS LOSS =

$\eta B^{1.6}$ ERGS PER C.C. PER CYCLE

AND IN WATTS =

$$W = \eta f B^{1.6} \times 10^{-7} \text{ PER CC.}$$

Hysteresis.—If a piece of iron is gradually magnetized and then slowly demagnetized it will be found that when the current is reduced to zero there is still some residual magnetism or remainance and the current has to be reversed to kill the flux. This is shown in the diagram and the complete circuit of magnetization is shown by the circuit ABCDEF. This lagging of the flux behind the magnetizing force is termed *hysteresis* and during a complete *cycle* as shown by the figure ABCDEF there is definite loss called the *hysteresis loss.*

In an alternating current machine this loss is continually going on and the actual loss depends on the actual iron used and various values, viz.

$$\text{Watts lost per c.c.} = nfB_{\text{max.}}{}^{1\cdot 6} \times 10^{-7}$$

where n is a coefficient depending on the actual material, the temperature, the flux density and the thickness of the laminations, f = frequency and $B_{\text{max.}}$ is the maximum flux-density.

Typical values for n are:

Cast steel	0·003 to 0·012
Cast iron	0·011 to 0·016
Soft iron	0·002
0·2 per cent. silicon steel	0·0021
3 ,, ,, ,, ,,	0·0016
4·8 ,, ,, ,, ,,	0·00076

Magnetic Paths in Series.—Where the magnetic part is made up of several different parts, the total reluctance of the circuit is obtained by adding the reluctance of the various sections. Taking the ring in the diagram, the total reluctance of this is found by calculating the reluctance of the iron part and adding the reluctance of the air-gap. The reluctance of the air-gap will be given by $\frac{l}{A}$, since μ is unity for air.

A.C. THEORY

Alternating Currents.—Modern alternators produce an E.M.F. which is for all practical purposes sinusoidal (i.e. a sine curve), the equation between the E.M.F. and time being

$$e = E_{max.} \sin \omega t$$

where e = instantaneous voltage
E = maximum voltage
ωt = angle through which the armature has turned from neutral.

Taking the frequency as f cycles per second, the value of ω will be $2\pi f$, so that the equation reads

$$e = E_{max.} \sin (2\pi f)t.$$

The graph of the voltage will be as shown in Fig. 1.

Virtual or Mean Value.—The average value of the voltage will be found to be 0·636 of the maximum value for a perfect sine wave, giving the equation

$$E_{A_v} = 0{\cdot}636 E_{max.}$$

The mean value is only of use in connection with processes where the results depend on the current only, irrespective of the voltage, such as electroplating or battery-charging.

R.M.S. (Root-mean-square) Value.—The value which is to be taken for power purposes of any description is the R.M.S. value. This value is obtained by finding the square-root of the mean value of the squared ordinates for a cycle or half-cycle. (See Fig. 1.)

$$E_{RMS} = E_{max.} \times \frac{1}{\sqrt{2}} = 0{\cdot}707 E_{max.}$$

This is the value which is used for all power, lighting and heating purposes, as in these cases the power is proportional to the square of the voltage.

Alternating Current Circuits.—*Resistance.*—Where a sinusoidal E.M.F. is placed across a pure resistance the current will be in phase with the E.M.F., and if shown graphically will be in phase with the E.M.F. curve.

The current will follow Ohm's law, viz. $I = \frac{V}{R}$, where V is the R.M.S. value of the applied E.M.F. or voltage and R is the resistance in ohms—the value of I will be the R.M.S. value. (See Fig. 2.)

Inductance.—If a sinusoidal E.M.F. is placed across a pure inductance the current will be found to be $I = \frac{V}{(2\pi f)L}$ where V is the voltage (R.M.S. value), f is the frequency and L the inductance in henries, the value of I being the R.M.S. value. The current will lag behind the voltage and the graphs will be as shown in Fig. 3, the phase difference being 90°. The expression $(2\pi f)L$ is termed the reactance (X).

Capacitance.—If a sinusoidal E.M.F. is placed across a condenser or other form of capacitance the current will be $I = (2\pi f).CV$, where C is the capacitance (capacity) in farads, the other values being as above. In this case the current leads the voltage by 90°, as shown in Fig. 4. The expression $\frac{I}{(2\pi f)C.}$ is termed the reactance (X) and current is given by

$$I = \frac{V}{X}.$$

Resistance and Inductance in Series.—In this circuit, shown in Fig. 5, the current will be given by $I = \frac{V}{\sqrt{R^2 + X^2}}$, where X is the reactance of the inductance $(X = (2\pi f)L)$. The expression $\sqrt{R^2 + X^2}$ is called the impedance (Z), so that $I = \frac{V}{Z}$. The current will lag behind the voltage, but the angle of lag will depend on the relative values of R and X —the angle being such that $\tan\phi = \frac{X}{R}$ (ϕ being the angle as shown in Fig. 5).

Resistance and Capacitance in Series.—For this circuit the current will be given by $I = \frac{V}{\sqrt{R^2 + X^2}}$, where X is the reactance of the capacitance $\left(\frac{1}{(2\pi f)C}\right)$. The current will lead the voltage and the angle of lead will be given by $\tan\phi = \frac{X}{R}$

Resistance, Inductance and Capacitance in Series.—The impedance (Z) of this circuit will be $Z = \sqrt{R^2 + (X_L - X_C)^2}$ with $I = \frac{V}{Z}$, and the phase difference will be either

$$\tan\phi = \frac{X_L - X_C}{R} \text{ or } \frac{X_C - X_L}{R},$$

ALTERNATING CURRENT CIRCUITS

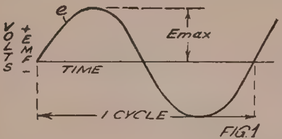


FIG. 1

- FREQUENCY = f OR $\sim$
- E_{max} = MAXIMUM EMF
- e = INSTANTANEOUS EMF
- i = " CURRENT
- V = RMS VOLTS
- I = RMS CURRENT
- X = REACTANCE
- Z = IMPEDANCE
- L = INDUCTANCE
- C = CAPACITANCE
- $\omega = 2\pi f$

$$I = \frac{V}{R}$$

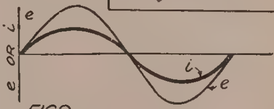
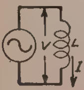
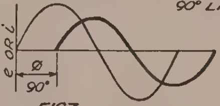


FIG. 2



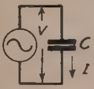
$$X = 2\pi FL$$

$$I = \frac{V}{X} = \frac{V}{2\pi FL}$$



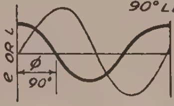
90° LAG

FIG. 3



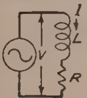
$$X = \frac{1}{2\pi FC}$$

$$I = \frac{V}{X} = 2\pi FCV$$



90° LEAD

FIG 4



$$Z = \sqrt{R^2 + X^2}$$

$$I = \frac{V}{Z} = \frac{V}{\sqrt{R^2 + X^2}}$$

ϕ = LAG

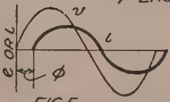
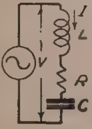


FIG. 5

$$\tan \phi = \frac{X}{R}$$



$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$I = \frac{V}{Z}$$

$$X_L = 2\pi FL$$

$$X_C = \frac{1}{2\pi FC}$$

FIG. 6

CURRENT LAGS IF $X_L > X_C$
CURRENT LEADS IF $X_C > X_L$
ANGLE OF LAG OR LEAD (ϕ) IS GIVEN BY

$$\tan \phi = \frac{X_L - X_C}{R} \text{ OR } \frac{X_C - X_L}{R}$$

whichever is the positive value. (Here X_L = inductive reactance and X_C = capacitive reactance.)

Power in A.C. Circuits.—The power in a single-phase circuit is given by $W = VI \cos \phi$, where W is the power in watts, V the voltage (R.M.S.) and I the current (R.M.S.). Cos ϕ represents the power-factor of the circuit, so that

$$\text{power-factor} = \cos \phi = \frac{W}{VI} = \frac{\text{watts}}{\text{volt-amperes}}.$$

Referring to Fig. 7, I represents a current lagging by angle ϕ. This current can be split into two components, OW, the energy component, and OR, the wattless component. Only the energy component has any power value, so that the power is given by $OV \times OW = OV \times OI \cos \phi = VI \cos \phi$.

Three-Phase Working.—The three windings of a three-phase alternator or transformer can be connected in two ways, as shown in Fig. 8. The relations between the phase voltages and currents and the line voltages and currents are indicated in this diagram. It should be noted that with the star or Y connection a neutral point is available, whereas with the delta or mesh connection this is not so. Generators are generally wound star and the neutral point used for earthing. Motors can be either star or delta, but for medium-voltage small-size motors a delta winding is usually used to reduce the windings.

Power in a Three-Phase Circuit.—The total power in a three-phase circuit is the sum of the power in the three phases. Taking the star system in Fig. 9 and assuming a balanced system (i.e. one in which the three voltages and currents are all equal and symmetrical), the total power must be 3 × power per phase. Therefore $W = 3.vi \cos \phi$. Substituting the line values for phase volts and phase current, we get

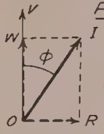
$$W = 3(vi.) \cos \phi. = 3\left(\frac{V}{\sqrt{3}} \times I\right) \cos \phi = \sqrt{3}.VI.\cos \phi.$$

It will be found that the same expression gives the power in a delta-connected system, and so for any balanced system the power is given by $W = \sqrt{3}.VI.\cos \phi$, where V and I are the line volts and line current and $\cos \phi$ represents the power-factor. For unbalanced or unsymmetrical systems the above expression does not hold good.

(Most three-phase apparatus such as motors can be assumed to form a balanced load, and calculations for current, etc., can be based on this assumption, using the above expression.)

ALTERNATING CURRENT CIRCUITS

POWER IN AN A.C. CIRCUIT



$W = VI \cos\phi$

$\cos\phi$ = POWER FACTOR

$= \dfrac{W}{VI} = \dfrac{\text{WATTS}}{\text{VOLTS}-\text{AMPS}}$

FIG. 7

OV = V = VOLTS
OI = I = CURREN
OW = ENERGY COMPT
OR = WATTLESS "

$OW = I \cos\phi$
$OR = I \sin\phi$

THREE-PHASE CIRCUITS (BALANCED SYSTEMS)

STAR OR Y

$V = \sqrt{3}\,v$

$I = i$

$W = \sqrt{3}\,VI \cos\phi$

DELTA OR Δ (MESH)

$V = v$

$I = \sqrt{3}\,i$

$W = \sqrt{3}\,VI \cos\phi$

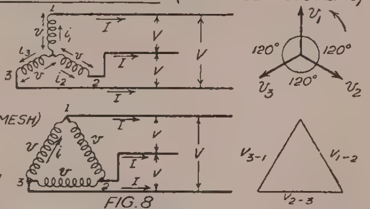


FIG. 8

3-PHASE 4-WIRE

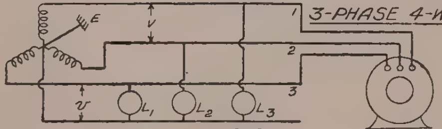
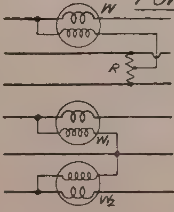


FIG. 9

L_1, L_2 AND L_3 ARE SINGLE-PHASE LOADS AT VOLTAGE v
THREE-PHASE LOADS ARE TAKEN FROM LINES 1, 2, & 3
AT VOLTAGE V NOTE:— $V = \sqrt{3}\,v$

POWER IN 3-PHASE



USE OF ONE WATTMETER FOR BALANCED LOAD. NEUTRAL IS OBTAINED BY USE OF RESISTANCE R

TOTAL POWER = 3 x W

TWO WATTMETER METHOD FOR BALANCED OR UNBALANCED LOADS

TOTAL POWER = $W_1 + W_2$

POWER FACTOR IS OBTAINED FROM

$$\tan\phi = \frac{\sqrt{3}\,(W_1 - W_2)}{W_1 + W_2}$$

FIG. 10

Power in a three-phase circuit can be measured in several ways. For permanent switchboard work a three-phase wattmeter unit is used in which there are usually two elements, so that the meter will indicate both balanced and unbalanced loads.

For temporary investigations either of the methods shown in Fig. 10 can be used. With a balanced load only one wattmeter is necessary providing an artificial neutral point is obtained by use of a resistance as shown. The total power = 3W where W is the reading on the single meter.

For an unbalanced load two units must be used, and these are connected as indicated in the diagram. In addition to giving the total power by adding the readings on the two meters, the power-factor can be obtained. It is important to note, however, that the reading of one meter will be reversed if the power factor of the system is less than 0·5. In this case the leads of one of the meters may have to be reversed in order to get a positive reading. For power factors of less than 0·5 the readings must be *subtracted* instead of added.

The power factor of the system can be obtained from the ratio of the readings. The simplest formula to use is

$$\tan \phi = \frac{\sqrt{3}(W_1 - W_2)}{(W_1 + W_2)}$$

which gives the tangent of the angle of lag, and the cosine can be obtained from the tables.

Power in Six-Phase.—In a six-phase system, such as is often used for rotary converters and other rectifiers, the power of the system (assumed balanced) is given by

$$W = 6.VI. \cos \phi$$

where V is the voltage between lines and I the line current.

Three-Phase 4-Wire.—The three-phase 4-wire system is now used in most districts for distribution purposes and the system is shown in the diagram Fig. 9. In this system there are three " outers " and a neutral. The voltage between any one " outer " and neutral is usually between 230 and 240 volts, and voltage between the " outers " is $\sqrt{3}$ times the voltage to neutral. This gives a three-phase voltage of approximately 400 volts for motors, etc. Single-phase loads are therefore taken from all " outers " to neutral and a three-phase load from the three lines marked 1, 2 and 3.

In the distribution cable the neutral may be either equal to the " outers " or half-size. Modern systems generally use a full-size neutral.

POWER FACTOR IMPROVEMENT

By Static Condensers.—The kVA required for power factor correction will be found by reference to the vector diagram on page 34. The load current is represented by OL_L lagging by angle ϕ_1, such that $\cos \phi_1$ is the power factor of the load.

Assuming that it is desired to improve the power factor to $\cos \phi_2$ by means of condensers, the resultant current must be represented by OI_R in the diagram.

To obtain this amount of correction the condenser current of OI_C must equal I_LI_R, and this value will be given by $OI_C = OI\ (\sin \phi_1 - \sin \phi_2)$.

The vector diagram is drawn for current, but is also applicable to kVA since the current is directly proportional to the kVA. Thus OI_L, OI_C and OI_R can be taken to represent the kVA of the load, the condenser and the resultant kVA respectively.

In this case the kVA of the condensers would be given by condenser kVA = load kVA $(\sin \phi_1 - \sin \phi_2)$. The kW load will be constant for condenser correction as the condenser current is assumed to be leading by 90°. Since OI_W is proportional to the kW load the equation with reference to the kWA is as follows:

$$\text{Condenser kVA} = \text{kW} (\tan \phi_1 - \tan \phi_2).$$

Actual Capacity Required.—It may be necessary to transform kVA capacity to microfarad capacity and the following relationship shows how this should be done.

Single Phase.—Current in condenser is given by

$I_C = 2\pi fCV$
I_C = current in amps.
f = frequency
C = capacity of condenser in farads
V = voltage
(*Note.*—1 farad = 10^6 microfarads.)

Three Phase.—The total line current taken by three condensers in delta is as shown in the diagram and is given by

line current = $\sqrt{3}$ phase current in each condenser.
Total line current = $\sqrt{3}(2\pi fCV)$.

WATTLESS AND POWER COMPONENTS FOR VARIOUS POWER FACTORS

Power Factor Cos Ø.	Angle Ø	Per kVA.		Per kW.	
		Power.	Wattless.	kVA.	Wattless Component.
1·0	0	1·0	0	1·0	0
0·98	11·48	0·98	0·20	1·02	0·20
0·96	16·26	0·96	0·28	1·04	0·29
0·94	19·95	0·94	0·34	1·06	0·36
0·92	23·07	0·92	0·39	1·09	0·43
0·90	25·83	0·90	0·44	1·11	0·48
0·88	28·37	0·88	0·48	1·14	0·54
0·86	30·68	0·86	0·51	1·16	0·59
0·84	32·87	0·84	0·54	1·19	0·65
0·82	34·92	0·82	0·57	1·22	0·70
0·80	36·87	0·80	0·60	1·25	0·75
0·78	38·73	0·78	0·63	1·28	0·80
0·76	40·53	0·76	0·65	1·32	0·86
0·74	42·27	0·74	0·67	1·35	0·91
0·72	43·95	0·72	0·69	1·39	0·96
0·70	45·57	0·70	0·71	1·43	1·02
0·68	47·15	0·68	0·73	1·47	1·08
0·66	48·70	0·66	0·75	1·52	1·14
0·64	50·20	0·64	0·77	1·56	1·20
0·62	51·68	0·62	0·78	1·61	1·27
0·60	53·13	0·60	0·80	1·67	1·33
0·58	54·55	0·58	0·82	1·72	1·40
0·56	55·93	0·56	0·83	1·79	1·48
0·54	57·32	0·54	0·84	1·85	1·56
0·52	58·66	0·52	0·85	1·92	1·64
0·50	60	0·50	0·87	2·00	1·73

The kVA is $\sqrt{3}$ VI so that the kVA

$$= \frac{3(2\pi f.C.V^2)}{1000}.$$

The C used in the above formula is the capacity of one of the three condensers forming the delta and so the total capacity is 3C. This gives us the formula :

$$\text{Capacity of each condenser} = C = \frac{\text{kVA} \times 1000}{3(2\pi f.V^2)}$$

$$\therefore \text{ Total capacity} = 3C = \frac{\text{kVA} \times 1000}{2\pi f.V^2}.$$

Synchronous Motor Correction.—Referring to the diagram on page 28, the current required for the synchronous motor cannot always be fixed by the desired amount of power factor correction, as in this case it is driving a load and the actual current will be fixed by the load on the synchronous motor and the power factor at which it is working.

It is impracticable to give formulae for working out these values as it is much better to start with the possible main load and the variable load which can be used for the synchronous motor.

Referring to the vector diagram, if values are taken either for currents as shown in the vector diagram or their proportionate kVA, their resultant current or kVA can be obtained as follows :

$$OI_R = \sqrt{(OI_L \cos \phi_1 + OI_C \cos \phi_2)^2 + (OI_L \sin \phi_1 - OI_C \sin \phi_2)^2}.$$

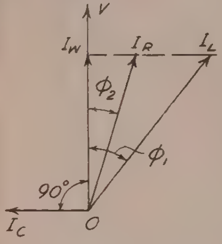
Resultant power factor can be obtained from

$$\tan \phi_3 = \frac{(OI_L \sin \phi_1 - OI_C \sin \phi_2)}{(OI_L \cos \phi_1 + OI_C \cos \phi_2)}.$$

If in any given case there is a fixed main load at a stated power factor plus a given kW load for the synchronous motor it is advisable to calculate the resultant power factor by working this out for various leading power factors for the synchronous motor.

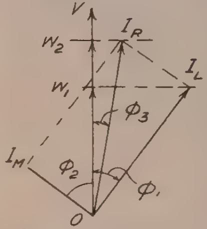
It should be borne in mind that synchronous and synchronous induction motors will not work satisfactorily at a very low power factor. Values between 0·6 and 0·9 leading are usually taken for satisfactory results.

POWER FACTOR CORRECTION



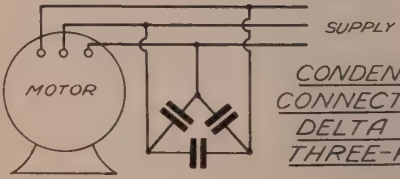
OI_L = LOAD CURRENT
OI_C = CONDENSER CURRENT
OI_R = RESULTANT CURRENT
$\cos\phi_1$ = LOAD POWER FACTOR
$\cos\phi_2$ = FINAL POWER FACTOR
OI_W = ENERGY COMPONENT
$OI_C = OI_L(\sin\phi_1 - \sin\phi_2)$

DIAGRAM FOR CONDENSERS



OI_L = MAIN LOAD CURRENT
OI_M = SYN-MOTOR CURRENT
OI_R = RESULTANT CURRENT
$\cos\phi_1$ = LOAD POWER FACTOR
$\cos\phi_2$ = SYN-MOTOR " "
$\cos\phi_3$ = FINAL " "
$OW_1 \propto$ ORIGINAL LOAD K.W
$OW_2 \propto$ FINAL LOAD K W

DIAGRAM FOR SYNCHRONOUS MOTOR



CONDENSERS CONNECTED IN DELTA FOR THREE-PHASE

The Financial Side of Power Factor.—The consumer pays for low power factor in two ways—first, on the initial cost of the installation; second, on the supply charges. Typical two-part tariffs for power users consist of a fixed, or maximum demand, charge of from £4 10*s.* to £6 per kVA of maximum demand, and a "unit" charge of from 0·4*d.* to 0·8*d.* or more per kWh of energy consumed.

Taking the case of the 300-kW loads, one at 0·9 and the other at 0·6 power factor, with a tariff of £5 per kVA, plus 0·5*d.* per kWh, and an annual service of 2,000 hours in each case, the annual bills from the supply company will be:

(1) For the 0·9 power factor load:

	£	s.	d.
333⅓ kVA at £5	1,666	13	4
300 × 2,000 kWh at 0·5*d.*	1,250	0	0
Total	£2,916	13	4

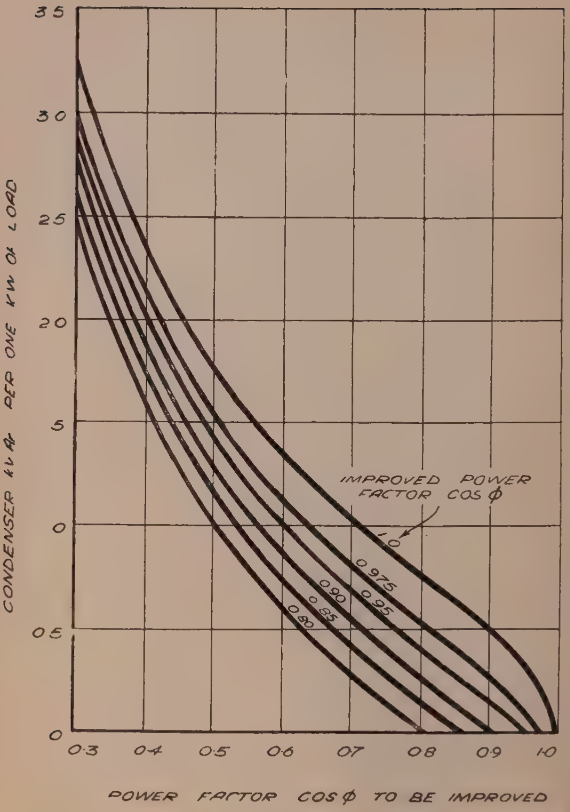
(2) For the 0·6 power factor load:

	£	s.	d.
500 kVA at £5	2,500	0	0
300 × 2,000 kWh at 0·5*d*	1,250	0	0
Total	£3,750	0	0

Thus the low-power factor consumer pays over £800 per annum on his electricity bill more than his high-power factor neighbour.

How the Bill can be Reduced.—The low-power factor consumer can reduce his bill by installing condensers to improve his power factor. If the power factor is to be improved to 0·9, a condenser of about 250 kVA will be required, which will cost between £500 and £700, according to the voltage. With this outlay the consumer will save from £100 to £300 during the year the condenser is installed, and £800 during each subsequent year.

These simple methods show how a decision can be arrived at as to whether an improved power factor obtained by the addition of correcting equipment is a financial proposition or not where a maximum demand tariff is in force. If a bonus and/or penalty system of charges is in force, the calculation of the reduction in power bill is obviously very similar to the above, while the calculation for the cost of improvement of power factor is, of course, the same.


CONDENSER KVA PER ONE KW OF LOAD
3 5
3 0
2 5
2 0
1 5
1 0
0 5
0
IMPROVED POWER FACTOR COS φ
1.0
0 975
0 95
0 90
0 85
0 80
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
POWER FACTOR COS φ TO BE IMPROVED

Examples on the use of SYNCHRONOUS CONDENSERS (Synchronous motors working at zero power-factor).

(1) Assume a load of 450 kilowatts at 0·65 power factor. It is desired to raise the power factor to 0·9. What will be the rating of the synchronous condenser ?

Solution.—We will assume we have to start with 450 kilowatts energy at 0·65 power factor, or

$$450 \times \frac{1}{0{\cdot}65} = 600 \text{ apparent kilovolt-amps.}$$

which has a component of $\sqrt{600^2 - 450^2} = 525$ wattless kilovolt-amps. lagging.

With the energy load unchanged and the power factor raised to 0·9, we will have $450 \times \frac{1}{0{\cdot}9} = 500$ apparent kilovolt-amps. which will have a component of $\sqrt{500^2 - 450^2} = 220$ wattless kilovolt-amps. lagging. It is obvious that the condenser must supply the difference between the 525 kilovolt-amps. and 220 kilovolt-amps. or 305 wattless kilovolt-amps. leading. A standard 300-kilovolt-amps. synchronous condenser would meet this case.

(2) It is desired to add 150 kilowatts load to the 450 kilowatts load at 0·65 power factor, but at the same time raise the power factor of the plant to 0·9. What will be the rating of the synchronous motor to supply this energy load and at the same time raise the power factor of the system from 0·65 to 0·9 ?

Solution.—We will have, as before, 450 kilowatts energy at 0·65 power factor, or, as we have 600 kilovolt-amps. with a wattless component of 525 kilovolt-amps., the energy load will be increased from 450 to $(450 + 150) = 600$ kilowatts and with the power factor raised to 0·9, we will have an apparent kilovolt-amps. of 670 with a wattless component of $\sqrt{670^2 - 600^2} = 300$ kilovolt-amps. Thus, we must supply in leading kilovolt-amps. the difference between 525 kilovolt-amps. and 300 kilovolt-amps. or 225 kilovolt-amps. The synchronous motor then must supply 150 kilowatts energy and 225 kilovolt-amps. wattless which would give it a rating of $\sqrt{225^2 + 150^2} = 290$ kilovolt-amps.

The actual input, of course, would be slightly greater than 290 kilovolt-amps.

THE ALTERNATING-CURRENT TRANSFORMER

The static transformer is based on the mutual induction between two coils wound on a closed iron circuit. The one, called the primary, is connected to a supply of alternating currents, and the other, the secondary, has an E.M.F. induced due to the changing flux established by the primary winding.

The simple single-phase transformer is illustrated diagrammatically in Fig. 1, the primary and secondary windings being marked.

The voltage ratio depends on the number of turns on the primary and the secondary, and will be given by $\frac{V_1}{V_2} = \frac{N_1}{N_2}$. Thus the ratio of the number of turns will give the voltage ratio of the transformer.

There are two main types of transformer: the core type and the shell type as shown in the diagram.

The core type, which is the more usual, has the advantage of being more easily repaired on site, whereas the shell type is more robust mechanically and gives better cooling for the iron.

Voltage and Flux Considerations.—In the ideal transformer it is assumed that the whole of the flux generated by the alternating E.M.F. in the primary links all the turns in the secondary. In practice a leakage coefficient allows for a variation from this ideal condition.

The relation between voltage and flux is given by the expression:

$$V = 4{\cdot}44 f N \Phi_m \times 10^{-8}$$

Where

f = frequency

N = number of turns (primary or secondary)

Φ_m = Maximum value of the flux.

Voltage Regulation of the Transformer.—The voltage ratio already given represents the ratio on no load, and when the transformer is on load there will be a fall in voltage due to the resistance of the primary and secondary windings and also due to magnetic leakage. The leakage flux is indicated in Fig. 2 and the leakage increases as the load increases. Thus the regulation increases as the load increases.

Equivalent Circuits.—The actual circuit of a transformer can be assumed to be as shown in Fig. 5, X_1 and R_1 being the primary values and X_2 and R_2 the secondary values. These can be formed into one circuit and the values referred to either primary or secondary. Referring the values to the primary we get

$$R = R_1 + R_2\left(\frac{N_1}{N_2}\right)^2$$

$$X = X_1 + X_2\left(\frac{N_1}{N_2}\right)^2$$

Referring the values to the secondary we get

$$R = R_1\left(\frac{N_2}{N_1}\right)^2 + R_2$$

$$X = X_1\left(\frac{N_2}{N_1}\right)^2 + X_2$$

To get the equivalent impedance Z we have—

$$Z = \sqrt{R^2 + X^2}$$

The values of R and X in the equivalent circuit can be obtained from the short-circuit test, which consists of sending a full load current through the transformer with either the primary or the secondary short circuited. A reduced voltage will, of course, be required owing to the short circuiting of one of the windings. Taking a 400/100 voltage transformer, the short-circuit test values measured on the secondary side might be as follows: 50 amperes (full load current) at 5 volts with a power input of 100 watts. From these figures, power factor $= \frac{100}{50 \times 5} = 0{\cdot}04 = \cos\phi'$. ($\phi'$ = internal phase angle.)

$$Z = \frac{V}{I} = \frac{5}{50} = 0{\cdot}1 \text{ ohm}$$

$$R = Z\cos\phi' = 0{\cdot}1 \times 0{\cdot}4 = 0{\cdot}04$$
$$X = Z\sin\phi' = 0{\cdot}1 \times 0{\cdot}916 = 0{\cdot}0916$$

Approx. volt drop = $IR\cos\phi + IX\sin\phi$.

Values for Unity Power Factor ($\cos\phi = 1$).

$$\text{V.D.} = 50 \times 0{\cdot}04 \times 1{\cdot}0 + 0$$
$$= 2 \text{ volts}$$

$$\text{Regulation} = \frac{2}{100} \text{ or 2 per cent.}$$

TRANSFORMERS

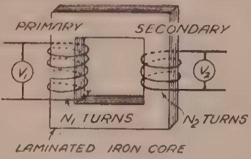


FIG. 1 SINGLE-PHASE TRANSFORMER

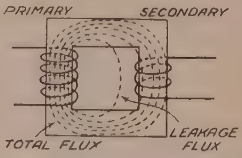


FIG. 2. DIAGRAM SHOWING LEAKAGE FLUX

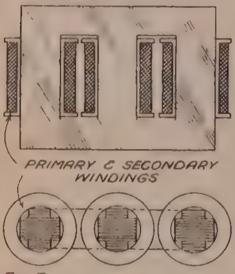


FIG. 3.— CORE TYPE 3-PHASE TRANSFORMER

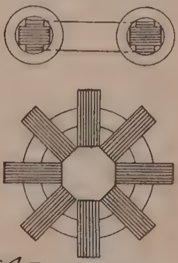


FIG 4 — CIRCULAR SHELL TYPE SINGLE-PHASE TRANSFORMER

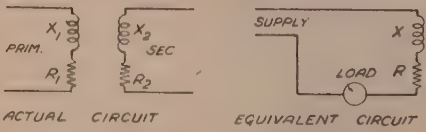


FIG 5 EQUIVALENT CIRCUIT VALUES —

REFERRED TO PRIMARY $R = R_1 + R_2 \times \left(\frac{N_1}{N_2}\right)^2$ $X = X_1 + X_2 \times \left(\frac{N_1}{N_2}\right)^2$

" " SECONDARY $R = R_1 \times \left(\frac{N_2}{N_1}\right)^2 + R_2$ $X = X_1 \times \left(\frac{N_1}{N_2}\right)^2 + X_2$

Values for 0·8 Power Factor ($\cos \phi = 0{\cdot}8$)

$$\text{V.D.} = 50 \times 0{\cdot}04 \times 0{\cdot}8 + 50 \times 0{\cdot}0916 \times 0{\cdot}6$$
$$= 4{\cdot}36 \text{ volts.}$$

$$\text{Regulation} = \frac{4{\cdot}36}{100} = 4{\cdot}36 \text{ per cent.}$$

Efficiency.

$$\text{Efficiency} = \frac{\text{output}}{\text{input}}$$

and this can also be written

$$\frac{\text{input} - \text{losses}}{\text{input}}$$

or

$$\frac{\text{output}}{\text{output} + \text{losses}}$$

The losses in a transformer are essentially very small and the efficiency of large transformers is over 99 per cent. Even with small transformers efficiency of 97 per cent. or 98 per cent. is usual.

There are two main losses in a transformer, namely, *the iron losses* and *the copper losses.* The iron losses are normally taken as constant, whereas the copper loss is proportional to the square of the load.

Taking the case of a 100-kilowatt transformer the losses might be taken as 800 watts iron losses and 1,200 watts copper losses. The efficiency at any other load can be obtained by making the copper losses proportional to the square of the actual load. Thus, on half-load the copper losses would be $1200 \times (\frac{1}{2})^2 = 300$ watts.

The total losses $= 800 + 300 = 1{,}100$; therefore efficiency

$$= \frac{50 \times 1000}{50 \times 1000 + 1100} = 97{\cdot}84 \text{ per cent.}$$

This compares with $\dfrac{100 \times 1000}{100 \times 1000 + 2000} = 98{\cdot}04$ per cent. for full load.

Parallel Operation.—For satisfactory parallel operation of transformers the following points must be watched:

A. The same voltage ratio.
B. The same phase displacement.
C. The same impedance pressure drop (or voltage regulation).
D. As nearly as possible the same internal phase relationship between resistance and reactance.

SUITABLE TRANSFORMERS FOR PARALLELING

	STAR / STAR	DELTA / DELTA	STAR / DELTA	DELTA / STAR	INTER-STAR / STAR	STAR / INTER-STAR
PRIM SEC STAR / STAR	YES	YES	NO	NO	NO	NO
PRIM SEC DELTA / DELTA	YES	YES	NO	NO	NO	NO
PRIM SEC STAR / DELTA	NO	NO	YES	YES	YES	YES
PRIM SEC DELTA / STAR	NO	NO	YES	YES	YES	YES
PRIM SEC INTER-STAR / STAR	NO	NO	YES	YES	YES	YES
PRIM SEC STAR / INTER-STAR	NO	NO	YES	YES	YES	YES

It will, of course, be evident that transformers in parallel must give the same secondary voltage for a common primary input.

The question of phase displacement will be seen from the diagram on page 36, which shows the types of windings which will run in parallel and which will not. A star delta transformer, for instance, will give a phase displacement of 30° and it is evident that this would not work in parallel with a transformer-wound star—star which has no phase displacement.

The question of voltage regulation is, of course, important, as this decides the proportion of the total load which is taken by each transformer.

The proportion of the load carried by each transformer also depends on the ratio between R and X in the two transformers.

When joining up transformers in parallel or paralleling supplies from two separate transformers it is, of course, important to check the phase rotation. This can be done either by a phase-rotation-indicating instrument or by lamps as used for synchronizing.

MERCURY-ARC RECTIFIERS

For many applications of power conversion the rotary machine has been superseded by the mercury-arc rectifier, a device which affords a direct conversion of energy without any intermediary mechanical stage as in rotary plant and which indeed is essentially static, with the consequent advantages of greater simplicity in construction and control, greater reliability and, in all but a few applications, higher efficiency.

The principle of the mercury-arc rectifier was discovered by Cooper Hewitt, who observed the rectifying properties exhibited by his Cooper Hewitt mercury-arc lamps, and his first patent leading to the practical utilization of this property dates back to about 1903. The first mercury-arc rectifiers were consequently of the glass-bulb type, and it is interesting to note that although other types of rectifier have been developed from it, the glass-bulb rectifier is still the most popular form in Great Britain, and is utilized for a surprisingly wide range of applications from battery charging up to supplying electric railway systems.

The first rectifiers were small and used on such minor tasks as battery charging. By 1914 single bulbs carrying 100 amps. and more were in service. After the War more rapid development took place and soon bulbs were produced to carry 500-600 amps. at voltages up to 600 volts. Bulbs operating at higher voltages such as 1,200 and 1,500 volts for traction and special H.T. bulbs operating at voltages of 20,000 to 30,000 volts for wireless applications are also now in common use.

Based on Cooper Hewitt's patents of 1908 and 1911, a simultaneous development of the steel-tank rectifier took place chiefly in America and on the Continent and subsequently, especially in the past eight or ten years, in Great Britain, where this type is now extensively manufactured.

The third type of mercury-vapour rectifier, the hot-cathode pattern, is of mixed origin, combining the electron-emitting properties of a heated filament (familiar in the wireless valve) with the property of mercury vapour to reduce the resistance of the electron path, the mercury vapour being obtained by introducing a small quantity of mercury into the bulb.

Principle of Operation.—In a rectifier the electron stream comprising the arc must be generated by some emitting source which may be the heated filament of the hot-cathode rectifier or, as in the case of the mercury-pool rectifier, the surface of the mercury cathode raised to incandescence by an arc. In practice this incandescence is first generated by drawing an arc from the mercury by means of a movable auxiliary electrode and this "hot spot" is subsequently maintained automatically by the action of the main rectifier arc, as explained later.

The hot spot serves a dual purpose:

(*a*) To maintain an atmosphere of mercury vapour inside the bulb.

(*b*) To provide a stream of free electrons.

If a positively charged electrode (anode) is placed near to the hot spot, the electrons from this source are attracted to the positive electrode at high velocity, and in this process collide with the mercury-vapour atoms from which further free electrons are thus liberated. These liberated electrons join the main electron stream which comprises the "mercury arc." The mercury-vapour atoms from which electrons have been liberated are left as (positively charged) ions which neutralize the negative space charge above the cathode (thus greatly reducing the resistance of the electron path) and also by bombardment of the cathode pool, due to mutual attraction, serve to maintain the incandescence of the hot spot.

By far the greatest flow of current will be from the cathode to the anode due to the large volume of the electron stream. A small, and for practicable purposes, negligible reverse current also occurs due to the relatively small number of ionized mercury-vapour atoms moving in the opposite direction. This unidirectional phenomenon is responsible for the valve action of the rectifier.

The neutralization of the space charge mentioned reduces the voltage drop in the arc to a constant value per unit length of arc path. For the usual sizes of rectifiers the value of voltage drop in the arc will be of the order of 15–30 volts.

The constant value of this voltage drop is responsible for an important feature of the rectifier as compared with rotating machinery in that the power loss in the rectifier increases directly and not as the square of the load current. This also explains the flatness of the efficiency curve for a rectifier.

MERCURY ARC RECTIFIERS

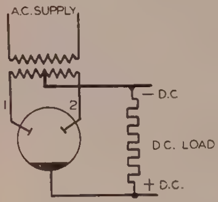
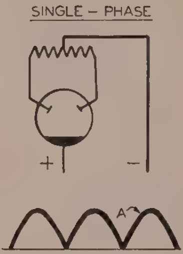


FIG. I
ESSENTIAL FEATURES OF SINGLE-PHASE RECTIFIER



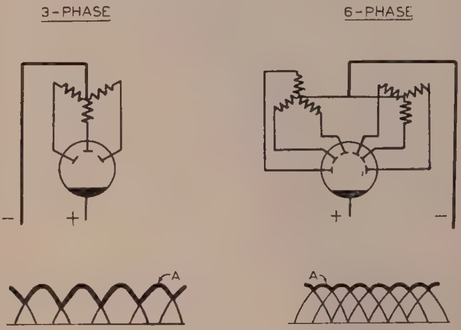


FIG. 2
THE HEAVY CURVES "A" SHOW OUTPUT WAVE FORMS NEGLECTING OVERLAP

The basic operation of the mercury-arc rectifier is simply illustrated in Fig. 1.

The A.C. supply is supplied to the rectifier bulb through a transformer of which the ends of the secondary winding are connected to the anodes (1 and 2) and the centre forms one pole (the negative) of the D.C. output. The ends of the transformer secondary (and therefore the rectifier anodes) reverse their polarity at the frequency of the A.C. supply, and assuming that the electron stream or arc has been initiated by auxiliary means as already mentioned, it will be attracted to the positive anode, and as each anode becomes positive in turn, so the arc will transfer from one to the other, since due to the repulsion effect of a negative anode on the (negative) electron stream and to the fact that the anode is not an electron-emitting source an arc cannot be sustained between the cathode and a negative anode.

It will be obvious, therefore, from the diagram that the electron flow will always be *from* the cathode to the (momentarily) positive end of the transformer winding, the effect of this being that the flow of current in the output circuit is always in the same direction, i.e. is direct current.

It will also be seen that an anode allows current to flow for only one half of each cycle (i.e. while it is positive with respect to the cathode).

By using a number of anodes in conjunction with suitable transformer connections, full-wave bi-phase, 3-phase, 6-phase, etc., rectification can be obtained. Fig. 2 shows representative connections and the unsmoothed D.C. wave form obtained with each.

Due to inductance in the circuit (in the transformer windings, etc.), the firing of each anode overlaps its neighbour, reducing the unsmoothed ripple to an R.M.S. value of about 66 per cent. of the average D.C. voltage in the case of biphase rectification, 25 per cent. in the case of 3-phase, 6 per cent. in the case of 6-phase, and 1 per cent. in the case of 12-phase rectification. All these values are very considerably reduced in practice by the inclusion of series smoothing chokes.

When employing 6-phase or 12-phase rectification, the rectifier transformer is most commonly connected in double or quadruple star or in fork. Multiple star connection is the simplest arrangement and by the employment of interphase transformers to couple the secondary star points, anode overlap can be doubled, thereby reducing the instantaneous value of the anode current with a corresponding reduction in heating

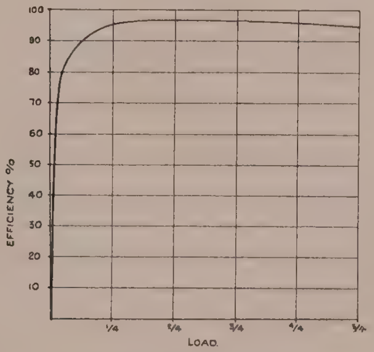
and better utilization of transformer windings. The inclusion of interphase transformers introduces a steep voltage drop of 15 to 20 per cent. from no load to about 1 per cent. load, but as a rectifier seldom operates on such a very low load this is rarely of importance. When necessary, this characteristic can be overcome by a modification of the interphase circuit or other means.

A rectifier, like a transformer, gives a constant and fixed output voltage which bears a direct ratio to the supply voltage. Means of controlling the voltage include the provision of a variable series resistance for small capacity plant, tappings on the rectifier transformer arranged either for on-load or off-load control, the provision of a separate induction regulator, and grid control. The latter entails the insertion of a metal " grid " in the arc path to each anode in close proximity to the anode. When the grid is at a potential negative to the cathode, the anode it controls is prevented from passing current even though it has a potential positive to the cathode. When a grid becomes positive to the cathode, the arc to the main anode controlled by it is able to start up, but once it has started up the grid has no further control over the arc and the anode will continue to carry current until it becomes negative to the cathode. Therefore, by retarding the point in the cycle at which the grid becomes positive to the cathode, the anode is caused to strike up later, resulting in a decrease of the average value of D.C. volts over a cycle. By suitably controlling the grids, the D.C. voltage may be varied from its maximum value down to zero.

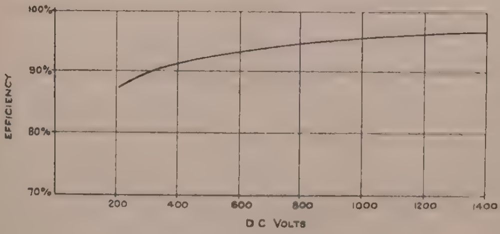
Construction of Various Types.—The construction of the three types of mercury arc rectifiers, which have tended to develop along different lines, will be briefly described :

A. Hot-Cathode Rectifiers.—Valves are now made in sizes up to 50 to 60 amps., though larger outputs can be obtained by paralleling several valves. The rectifier normally consists of a valve or valves, air- or oil-cooled transformer which may be either double wound or auto, and a delay device to allow time for the valve filaments to heat up before load is taken. Switches and meters, etc., can be provided as required, and the whole assembly is usually enclosed in a metal case. Due to the short arc path, the efficiency is high and the filaments of modern valves have a life of several thousand hours. It must be noted, however, that their life, while long, is definitely limited by that of the filament,

MERCURY ARC RECTIFIER EFFICIENCY CURVES



TEST EFFICIENCY CURVE OF 12 PHASE
1500 VOLT D.C 1200 K W. RECTIFIER



CURVE ILLUSTRATING INCREASE IN EFFICIENCY
WITH INCREASING D.C. VOLTS.

BY COURTESY OF HEWITTIC ELECTRIC C^{o} L^{TD}

involving replacement of the valve at intervals, a point which should receive due consideration with the purchase price. These rectifiers are widely used for battery charging and for feeding small cinema arcs and other low-power applications.

B. Glass-Bulb Mercury-Pool Rectifiers.—Bulbs are made in sizes from 10 amps. to 600 amps. and there are glass-bulb rectifier substations in service giving up to 14,000 amps. at 500 volts, i.e. 7,000 kW, obtained by a compact banking (paralleling) of a number of rectifier units. The splitting up of a large substation capacity into a number of smaller parallel units in this manner has definite advantages in giving increased reliability since if one unit fails the remainder will normally continue to function until the faulty unit receives attention.

In small sizes of up to 100 amps. or so, an air-cooled transformer is situated in the same sheet-metal cubicle as the bulb and excitation gear. A fan may be provided to cool the bulb at its higher ratings. In larger sizes, the transformer is oil immersed in a tank standing alongside the bulb cubicles. Each of the bulbs is mounted in a special cradle in a cubicle with anode fuses and reactors, fan motor and excitation gear of a typical rectifier unit manufactured by the Hewittic Electric Company of England. Rectifiers of this type are able to withstand heavy overloads, which together with their high efficiency has made them particularly prominent in the traction field supplying trolley buses, electric trains, etc. Typical efficiencies are shown on page 48 and standard overloads are given in the following table:

25 per cent. for 2 hours
or 50 per cent. for 15 minutes
or 100 per cent. momentarily

These overloads are standard as called for by B.S.I.

The steel cubicle units in which the glass-bulb rectifiers are constructed lead to a compact arrangement, easily installed without need of special foundations and comparing favourably in the matter of floor-space even on large installations with their rivals in this latter field, the steel-tank rectifier. Operation of the glass-bulb rectifier is extremely simple. The A.C. circuit-breaker may normally be left closed (although the A.C. supply must be isolated if the cubicle is opened for inspection or maintenance) and putting the rectifier into service involves merely the closing of the D.C.

THE STARTING CIRCUIT.

Operation and Adjustment.

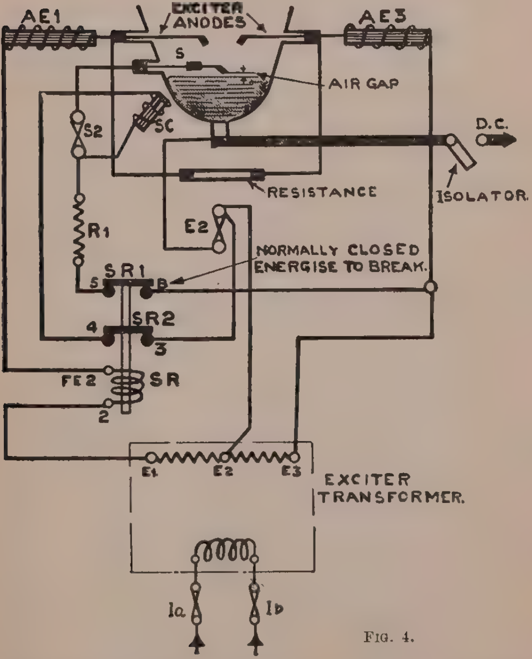


FIG. 4.

Starting Operation. Starting electrode S is magnetically attracted by starting coil SC and makes contact with mercury.

S then short circuits SC and S is released.

On leaving the mercury an arc is formed and exciters AE1 and AE3 will strike up.

Exciter current passes through coil SR, opening relay SR and disconnecting starting circuit.

circuit-breaker. A study of the circuit diagram (Fig. 4) will show that when this circuit-breaker is closed the cathode "hot spot" is automatically initiated by means of the ignition electrode and the arc is then maintained by means of the exciter electrodes, which comprise in effect a very small single-phase rectifier within the main bulb and whose object is to maintain the cathode hot spot and the necessary mercury-vapour atmosphere inside the bulb, even though there is no load on the main anodes. As soon as the load comes on to the rectifier the main anodes come into operation, the arc to these becoming brighter as the load increases. The whole of this operation is entirely automatic.

It is important to note that while the first cost of the glass bulbs used in this type of rectifier may appear relatively high, nothing is consumed in the bulb, the vapourized mercury merely condensing in the upper part of the bulb and flowing back to the cathode, so that the useful life of the bulb is indefinitely long, extending in a great many cases to over 10 years. Statistics of one Company show that in over 500,000 kW of Hewittic rectifiers installed over a period of 15 years, 97 per cent. of the original bulbs are still in service, a significant comment on both the long life and robustness of these units.

C. Steel Tank Mercury-Pool Rectifiers.—These are essentially high-capacity rectifiers and are made for outputs of about 200 amps. and upwards to 6,000 amps. or more in a single unit. The smaller sizes from 200 to 500 amps. are air cooled and mounted in cubicles in a similar fashion to glass bulbs, while the larger units usually having 12, 18 or 24 anodes are erected on special foundations in a substation, and provided with water cooling. Until recently, due to the slightly porous nature of the steel tank and its insulated seals, it was necessary to have a rotary vacuum pump, automatically controlled by the state of the vacuum inside the rectifier. Recent developments have now produced for the smaller sizes a tank of special steel fitted with non-porous vitreous enamel seals, which is claimed to hold its vacuum indefinitely. Steel-tank rectifiers have been used mainly for traction loads, and their efficiency is rather below the efficiency of an equivalent capacity of glass-bulb units, due to the longer arc-path necessitated and small additional losses from running auxiliaries such as vacuum and water pumps.

Performance and Characteristics of Mercury-Arc Rectifiers.—The main source of power loss in a mercury-arc

rectifier occurs in the mercury arc itself. The arc resistance varies little, however, and hence the efficiency of a rectifier increases with the output voltage, as shown on page 43. For this reason also the efficiency is almost constant from very light loads to very heavy overloads, a typical curve being shown on the same page.

The inherent voltage regulation depends upon the reactance of the rectifier transformer. A usual minimum value is 5 per cent. to 6 per cent. from light load to full load, though the regulation may be increased to any desired value by the inclusion of reactance in the anode circuits.

The power factor is a function of the number of phases, but it also depends on the anode and transformer reactance and the load current. Average power factors obtained at full load are 0·86 for bi-phase, 0·83 for 3-phase, 0·93 for 6-phase, and 0·95 for 12-phase connections.

The usual tests carried out on mercury-arc rectifiers include the measurement of the no-load losses and the voltage regulation. Efficiency is most accurately assessed by adding the losses of the transformer and rectifier to the output to give the input power.

Interference Suppression.—Consequent on the nature of the process of rectification, a small A.C. component or ripple is always superimposed on the D.C. output. With the usual smoothing chokes employed, this is not sufficiently prominent to interfere with most electrical machinery. Rectifiers are occasionally found to interfere with wireless reception due to local conditions. The interference may be either low frequency, detected by a continuous background hum in a loud speaker, or hign frequency, giving a continuous crackling or mush which drowns reception on certain wavebands only. L.F. interference is due to the alternating harmonics superimposed on the D.C. voltage and is eliminated at the source by suitably designing the rectifier transformer or by the addition of a tuned filter circuit to the rectifier. H.F. interference is easily disposed of either at the source or at the receiver by earthing each main through a 1 mfd. condenser.

Special Applications.—Mercury-arc rectifiers have been used for some years to supply the anodes of radio transmitting valves, and similar applications at pressures as high as 20,000 and 30,000 volts. They can also be used as invertors for transferring power from a D.C. to an A.C. network and a few

such installations are in service. Their application in this respect is, however, limited to some extent by instability of operation and the short period of each cycle during which load can be carried, resulting in a rather poor output wave-form.

Installation and Maintenance.—(*a*) *Hot Cathode Type.*—The filament current should be checked when this type of rectifier is commissioned and also on subsequent occasions when it is cleaned. Very little attention is needed but, as with all electrical equipment, it is recommended that a periodical inspection should be carried out to ensure that the connections are tight and to remove dirt, etc.

Should the rectifier fail to operate, examination should be as follows:

(1) Check the A.C. supply;
(2) Check the fuses;
(3) Examine the filament;
(4) Overhaul the transformer and other connections.

Towards the end of its life the valve output will tend to fall away due to the exhaustion of the filament emitting surface, and it will then be necessary to replace the valve.

(*b*) *Glass-Bulb Mercury-Pool Type.*—With the glass-bulb rectifier special foundations are not necessary except in the largest sizes, where these may be required for the transformer only due to its weight. The rectifier cubicles are normally despatched from the maker's works complete (apart from the bulb, which is generally packed separately), and after the cubicles have been placed in position they may be bolted and possibly grouted to the floor.

The transformer is sometimes, though not usually, placed outside the building housing the rectifier cubicles, and in this case the cabling between transformer and rectifier will usually take the form of P.I.L.C. with sealing glands. For wholly indoor installations, cabling may be of the usual types for such purposes, i.e. V.I.R., cambric covered, etc., to suit requirements.

After installation of the equipment is complete the bulbs are installed and when each bulb is settled in its cradle the position of the starting electrode should be checked. With the starting coil de-energized the electrode should hang about $\frac{1}{4}$ inch above the mercury and when the coil is energized the electrode should touch the mercury.

If a fan is fitted, check that the bearing grease-caps contain grease. These caps should be given a turn about every

1,000 running hours to keep the fan motor lubricated. This operation represents the only service normally necessary for this type of rectifier which, generally speaking, requires no attention. As with all electrical plant, however, an occasional inspection should be made to ensure that connections are firm and to remove any loose dust or dirt.

The bulb-arm connections are normally locked by lock-nuts, and should need no attention. In connecting up or removing a bulb, however, care should be taken not to wrench or twist the connection caps at the ends of the arms. The clip connector should be loosened and slipped straight on or off the cap without a twisting action and tightening should be done firmly but gently.

In the event of the rectifier failing to start

(1) Check the A.C. supply ;
(2) Examine the fuses ;
(3) Check the connections and the transformer voltages;
(4) Check the operation of the exciter circuit ;
(5) Examine the bulb to ensure that condensed mercury is not clinging to the condenser chamber, thus lowering the level in the pool. This is unusual but is occasionally caused by continuous running on light load at low temperatures.

(c) *Steel-Tank Mercury-Pool Type.*—A steel-tank rectifier requires good solid foundations due to its much greater weight than other types, and also an adequate supply of water for cooling purposes.

Having installed the rectifier, together with the auxiliary pumps and circulators, the rectifier chamber must be conditioned. This is commonly done by supplying the rectifier at a considerably reduced voltage with the vacuum pumps operating. This preliminary conditioning liberates the occluded gases from the metal, which gases are evacuated by the vacuum pumps. The time necessary for conditioning is stated by the various makers for their own equipment.

When the rectifier has been conditioned the vacuum gauge must be watched with the pumps shut down to ensure that there are no leaky seals or joints. If all is satisfactory the rectifier can be switched in with the full A.C. supply to the anodes and put on load.

During use the vacuum pumps must be maintained in perfect condition and the water circulation arrangements regularly examined. Care should be taken that hard water is not used for the water-jacketting of the rectifier

Should the rectifier shut down with the A.C. supply still on, examine :

(1) The vacuum gauge.

If loss of vacuum is indicated, examine :

(2) The vacuum pump and seals.

If, however, the vacuum is high, examine :

(3) The water-cooling system including the circulator.

If the rectifier and auxiliaries appear to be in order it is probable that the rectifier has merely tripped out on overload. To return it to service ensure that the D.C. breaker is open, then close the A.C. breaker, and if everything appears to be normal, close in the D.C. breaker. Should the A.C. protective gear on one or more phases trip on no-load, however, the trouble is serious and, particularly on a rectifier that has been in service for some years, may be the result of failure of internal insulation, due sometimes to this becoming coated with a thin film of iron as a result of the operation of the rectifier.

CONVERTING MACHINES

The term converting machines is used to cover those arrangements whereby A.C. is converted to D.C. by machines having rotating parts. There are three main types as follows :

Rotary Converters

These consist of a wound rotor revolving in the field of a D.C. generator, the rotor being fitted with slip-rings at one end and with a commutator at the other. If while rotating at synchronous speed an A.C. supply is connected to the slip-rings, D.C. can be taken from the commutator. There is only one winding and the power to keep the machine running and to supply the electrical and friction losses is taken from the A.C. side.

A rotary converter will run from the D.C. side when A.C. can be taken from the slip-rings—this arrangement being called an *inverted rotary converter*. Practically all rotary converters of any size are polyphase—three-phase for small and medium outputs and six-phase for larger outputs.

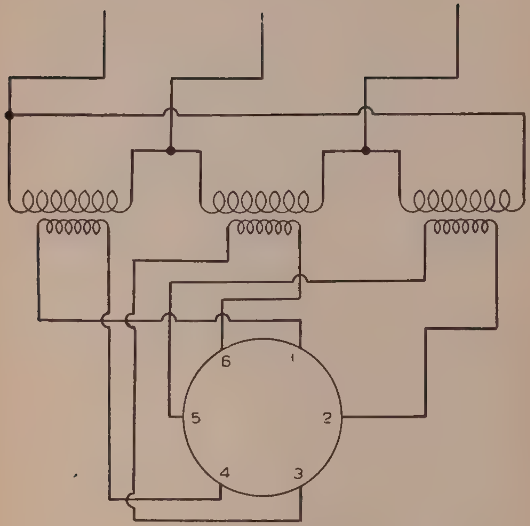
Ratio of Transformation.—The D.C. voltage will be $\sqrt{2}$ or 1·41 times the A.C. voltage for a single-phase and the various ratios for polyphase machines are given in the following table :

	Single Phase.	Three Phase.	Six Phase.	Twelve Phase.
Volts between slip-rings as a percentage of D.C. Volts . . .	70·7	61·2	35·4	18·3

The relationship is given by A.C. volts between slip-rings $= \dfrac{\text{D.C. volts}}{\sqrt{2}} \sin \dfrac{\pi}{m}$ where m = no. of slip-rings.

As D.C. voltages are usually in the region of 220 to 240 volts it will be seen that with normal A.C. supply a transformer is required to give the required pressure for the supply to the A.C. side.

Six-phase machines are the most usual since it is fairly simple to obtain a six-phase supply from the secondary of



SIX-PHASE CONNECTIONS.

Diagram shows one method of obtaining six-phase from a standard three-phase supply.

the transformer, a diagram of connections being shown on the opposite page.

Voltage regulation is obtained either by varying the power factor (by excitation control), thus using the reactance of the transformer, or by using a booster. Voltage control can also be obtained by using an induction-regulator.

The efficiency of a rotary converter varies from 90 to 94 per cent.; it has a high overload capacity, and as the power factor is under control it can be kept round unity.

Normally, rotary converters are not self-starting from the A.C. side, but a starting winding can be wound on the *stator* to act as an induction motor. Other methods include starting from the D.C. side and the use of an auxiliary starting motor. With these methods careful synchronizing is necessary before switching on to the A.C. supply.

Motor Generators

These consist of two entirely separate machines (from the electrical point of view), and any two machines—a motor driving a generator—form a motor converter.

Normally they are coupled machines for converting A.C. to D.C. and consist of either an induction motor or a synchronous motor driving a D.C. generator. They also convert in the reverse direction from D.C. to A.C. when the latter is required where there is no supply. Also motor converters are used as frequency changers—an A.C. motor driving an alternator.

As there are losses in both machines the efficiency is not high and not usually above 90 per cent. One of the advantages is that high-tension can be taken to the A.C. side and a wider control is obtainable as to the voltage on the output side than with rotary converters.

Motor Converters

These consist of two machines mechanically coupled together but also connected electrically. The motor portion consists of an induction motor with a wound rotor, the rotor being connected to the winding of the rotor of the generator portion. The efficiency at full load varies from 86 to 92 per cent. with a power factor of 0·95 and over. They are rather more stable than rotary converters and are self-starting from the A.C. side. They are not quite so efficient at light loads.

METAL RECTIFIERS

A. Description.—Copper discs or plates are processed to form a layer of oxide on the surface of the copper, when it is found that the electrical resistance, measured from oxide to copper, is low, but is high when measured in the opposite direction. The ratio of resistances is of the order of 1 : 1,000. The action is not fully understood, but apparently rectification occurs at the junction of the oxide and copper. No chemical action takes place.

A number of active cells are assembled, together with cooling fins, and connectors, on a spindle, the cells being arranged in series or parallel as required. Good contact to the oxide surface is obtained by means of metal spray or by pressure.

The rectifier is entirely static and withstands severe vibration. It is silent and produces no interference with radio. The chief feature lies in the elimination of all maintenance, no attention whatever being required.

B. Range of Sizes.—The range of practical sizes, with their usual duties, is of interest.

400,000	volts	at	10 milliamperes	for X-ray work
60,000	,,	,,	0·25 ampere	for electrostatic precipitation
5,000	,,	,,	2 amperes	for anode supply to transmitting valves
600	,,	,,	5 amperes	
400	,,	,,	10 ,,	for general D.C. supply
230	,,	,,	25 ,,	
100	,,	,,	75 ,,	for battery charging
6	,,	,,	12,000 ,,	or more, for electro-deposition.

The smallest sizes built are used with moving-coil instruments for reading A.C. pressures and currents, the actual rectifier delivering 1 milliampere at about 200 millivolts, while a special rectifier for use in radio receivers at frequencies of 1,500 kilocycles to handle 100 micro-amperes has also been developed.

Larger currents at the various voltages may be justified under unusual conditions.

C. Circuits.—Several circuits have been devised as being the most economical to employ under various circumstances. The rectifier is shown as an arrow mark in the diagrams, current flowing in the direction of the arrow-head but not in the opposite sense. (When more than one arrow-head is shown, the combination is built as one complete unit.)

Diagrams showing the voltage and current wave-forms, and how they should be measured, are included. Great care must be exercised in selecting the correct type of instrument, i.e. moving-coil or moving-iron, or misleading results will occur.

The economical sizes of the rectifiers employed in the various circuits, and the purposes for which they are supplied, are as follows:

Ref. 1.—D.C. selection by change of polarity of supply. Outputs up to 50 watts. Mainly used with telephone type relays in G.P.O. circuits.

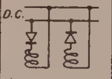
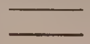
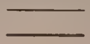
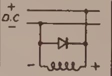
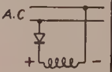
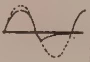
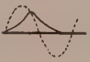
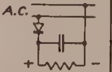
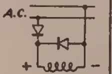
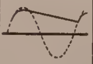
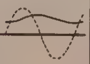
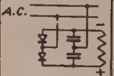
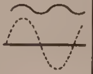
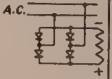
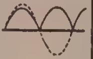
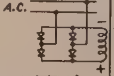
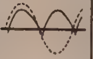
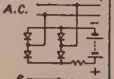
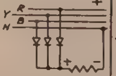
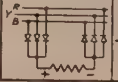
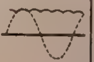
Ref. 2. Surge Absorber.—When the solenoid—such as the field system of a large alternator—is energized, there is a negligible leakage of current through the rectifier. When the solenoid is switched out of circuit, the inductive energy allows the current to die down gradually, without any pressure surge, by flowing in the closed circuit formed by the rectifier and solenoid. The flux gradually collapses, so the principle is often used as a time delay action. Relays shunted with rectifiers will hold up for about a second after the power is cut off.

Ref. 3. Half-Wave.—The only application of this current is in connection with vibrating screens, employed for sieving coal, stone, etc.

Ref. 4. Half-Wave and Capacity.—The economical output depends on the current rather than the watts required—50 milliamperes at voltages between 100 and 5,000 being the maximum. The system is often applied to radio receivers designed to operate on A.C. or D.C. mains, and for small contactors or relays requiring about 5 watts when energized from 230-volt A.C. mains.

Ref. 5. Series Shunt.—A large inductance is essential to this system—an air-gap in the iron circuit, as in a contactor, may make the circuit inoperative. Outputs up to 25 watts are economical.

Ref. 6. Voltage-Doubler.—Used extensively for the H.T. supply for radio receivers, requiring 100 milliamperes at 350 volts. Also used in D.C. pressure-testing sets, delivering 10 milliamperes at up to 50,000 volts.

REF.	DESCRIPTION	CIRCUIT DIAGRAM	WAVE FORM		CORRECT INSTRUMENTS	
			VOLTAGE ACROSS LOAD	CURRENT THRO' LOAD	VOLTAGE	CURRENT
1	D. C. SELECTOR				M. C. OR M. I.	M. C. OR M. I.
2	SURGE ABSORBER				M. C. OR M. I.	M. C. OR M. I.
3	HALF WAVE				M.C x 2	M.C x 2
4	HALF WAVE AND CAPACITY				M.C.	M.C.
5	SERIES SHUNT				M.C.	M. I.
6	VOLTAGE DOUBLER				M.C.	M.C.
7A	SINGLE PHASE RESISTANCE LOAD				M. I.	M. I.
7B	INDUCTIVE LOAD				M.C.	M. I.
7C	BATTERY LOAD				M. C. OR M. I.	M. C.
8	THREE PHASE HALF WAVE				M. I.	M. I.
9	THREE PHASE FULL WAVE				M. C. OR M. I.	M. C. OR M. I.

Ref. 7. Bridge.—This circuit is used in the majority of instances where D.C. power is required. The voltage and current wave-form under various conditions of loading are shown. The most common types of load characteristic are inductive (see 7*b*) and battery charging (7*c*). A filter system is not required when relays, magnet coils, etc., or other small solenoids are energized from a single-phase bridge rectifier as there is generally sufficient inductance to smooth the current wave so as to prevent chatter.

When charging batteries, some form of ballasting is necessary, or the charge rate will be widely influenced by small changes in the supply pressure. A resistance is shown in Fig. 7*c*; a choke is used on large chargers, giving higher efficiency and a smoother current wave.

Ref. 8. Three-Phase, Half-Wave.—This circuit is rarely used—occasionally for short-time rated rectifiers for closing oil-circuit breakers.

Ref. 9. Three-Phase, Full-Wave.—This is economical, compared with single-phase full-wave, above 1 kilowatt, but is often used for lower powers when the output is to be smoothed, the reduction in ripple allowing considerable saving in the cost of the filter.

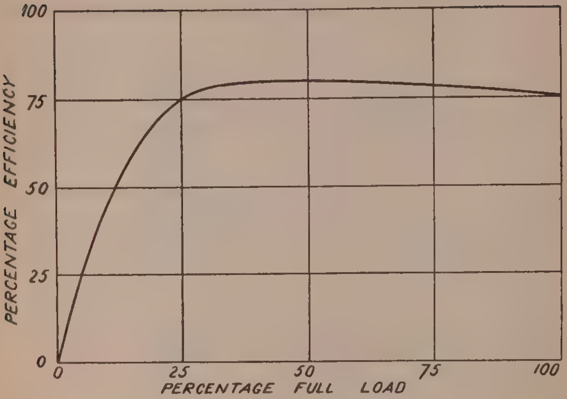
D. Efficiency.—The efficiency curve is peculiar in that it reaches its peak at about one-third load and does not drop appreciably. The input and output figures should be calculated in watts, to show the actual losses in the rectifier, but when battery charging is concerned, the useful output is the product of mean volts and mean amperes. This is less than the figure of watt efficiency which includes the ripple component dissipated as heat in the battery and leads, not contributing to the chemical action.

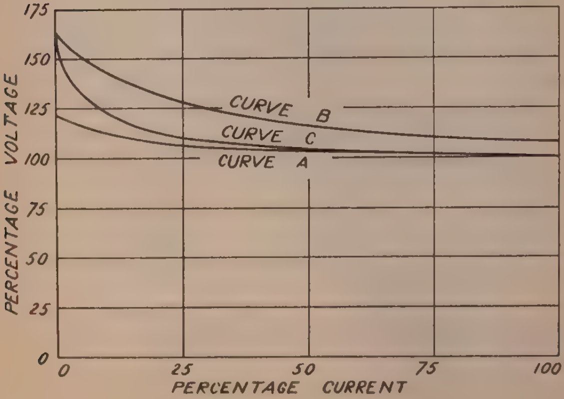
E. Life.—Westinghouse rectifiers, which have been in continuous use for nearly ten years, still operate satisfactorily. There is a slight reduction in output during the first few months, after which output stabilizes. The reduction in output is so small that it can be neglected under most conditions.

F. Regulation.—The regulation curves with various types of loading are shown on page 58.

Curve A shows that of a bridge-connected single-phase rectifier feeding a resistive or inductive load. The voltage rise from full load to no-load is about 20 per cent., but only

METAL RECTIFIERS
Performance Curves





10 per cent. down to 25 per cent. full load. Special compensating circuits are sometimes used to maintain constant D.C. voltage with varying load.

If a condenser is shunted across the rectifier, the open-circuit voltage rises to the peak value of the A.C. input pressure. Curve B shows the effect of adding capacity to the current.

To reduce the steep regulation resulting when reservoir capacity is used, a choke is sometimes connected directly after the rectifier, when the regulation is as shown in Curve C.

G. Ventilation and Forced Cooling.—The air temperature around a rectifier should not exceed 100° F. (38° C.) unless it is specially rated to operate at a higher temperature. 125° F. is about the safe limit of temperature.

Forced cooling by fans increases the capacity but is not economical below about 2 kilowatts output. Care must be taken to ensure even distribution of cooling air or the load will be unevenly shared.

H. Intermittent Ratings.—A rectifier reaches its working temperatures in about 15 minutes, but cools slowly owing to the small temperature difference. Intermittent ratings are practicable when the rectifier is allowed to cool between periods of load, by disconnection from all sources of power. Outputs of 25 kilowatts at 400 or 230 volts have been obtained commercially for closing solenoid-operated oil-circuit breakers, rated at 30 seconds per hour.

HOT CATHODE VALVE RECTIFIERS

THE principle of the high vacuum rectifying valve such as is used in radio receivers for supplying D.C. current from A.C. mains is well known.

The valve consists of an electron emitting cathode surrounded by an anode. The anode is generally coated with a mixture of barium and strontium oxides and heated by passing a current either through it directly, or through a separate heater which it surrounds but from which it is insulated.

If a positive potential is applied to the anode, electrons are attracted to it and a current passes, the magnitude of which depends upon the anode potential up to a value equal to the total electron discharge of the cathode. This is the saturation current, and a further increase of anode potential will not cause any increase of current.

The total amount of current in this type of valve is relatively small and it has a high impedance owing to the "space charge," viz. the cloud of electrons which surround the anode. The electrons which are farthest from the cathode tend to repel the others back towards the cathode and thus partly neutralize the pull exerted by the positive anode. Fig. 1 (*a*) shows the characteristic curve of this type of valve.

If a small quantity of an inert gas, such as argon, helium, neon or mercury vapour, be introduced into the valve, quite a low potential, viz. 8 to 15 volts on the anode, is sufficient to ionize the gas, this ionization being due to collision between the gas molecules and the electrons given out by the cathode. The positive ions thus formed travel towards the cathode and neutralize the space charge. A much larger current can therefore pass for a given anode potential. The passage of the current is accompanied by a visible glow, the colour of which depends upon the particular gas used.

The impedance of the valve falls to zero and may even become negative. The voltage drop across the tube being practically constant for all loads, it follows that the current passed by the valve depends only upon the impedance of the circuit; Fig. 1 (*b*) shows the typical characteristics of a gas discharge tube. As the mass of the positive ions is very much greater than that of the electrons, their movement is much slower and they contribute but little to the total current, which is almost entirely carried by the electrons.

This sets a limit to the maximum current that can be taken from a gas discharge valve, and it must never exceed the saturation emission of the cathode or bombardment of the emissive surface by positive ions will take place, due to the lack of sufficient electrons to neutralize them.

If the excess of current is great, visible sputtering takes place and sparks are emitted from the cathode. In the case of smaller overloads the sputtering may be invisible, but damage nevertheless ensues and the life of the valve is materially shortened, consequently the peak current must never exceed that specified by the makers.

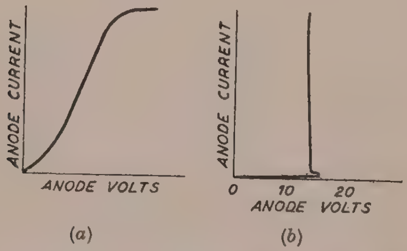


Fig. 1.—Characteristic Curves of a High Vacuum Rectifying Valve and a Gas Discharge Tube.

(a) High vacuum rectifying valve ; (b) Gas discharge tube.

One consequence of this is the necessity of heating the cathode to its operating temperature before the anode circuit is closed. This pre-heating time may, in the case of independently heated and shielded cathodes, be as much as 15 minutes in the mercury discharge type. In the case of the gas discharge tubes it is usually of the order of 30 to 60 seconds. Unfortunately there is no way of avoiding this delay. Time delay switches can be used to make the switching in of the load automatic at the expiration of the required interval.

The gas pressure is very important as a decrease of pressure will reduce the probability of collision and increase the voltage drop across the tube, and bombardment of the cathode will result. There is a critical voltage drop within which the tube must be designed to operate. On the other hand, if the pressure is too high the voltage at which the tube will spark over in the inverse direction is lowered, thus setting a limit on the maximum voltage that can be rectified.

In the case of valves filled with a gas the pressure can vary but little, but where mercury is used, the mercury being in the form of a small globule introduced during evacuation, the pressure will depend on the temperature of the coolest part of the tube, and the maximum inverse voltage that the tube will stand is simply a question of design.

In the case of gas-filled tubes with two or more anodes which are required to give an output of the order of 230/250 volts D.C., the anodes are often placed in separate limbs fused on to the main body of the tube in order to prevent flash over from anode to anode. This type of design sets a limit on the minimum voltage at which the arc will strike. This is of importance only when the load contains a back E.M.F. Such tubes are often constructed with an auxiliary anode which is connected to a small auxiliary rectifier supplying smooth D.C., the current take being of the order of 20 milliamperes. This anode maintains the arc irrespective of the nature of the load.

The fact that gas and mercury discharge tubes have no internal resistance is of great importance, as the regulation becomes practically that of the transformer and a circuit can be designed giving a constant voltage over a wide range of current output.

This absence of resistance in the tube makes rectifiers of high efficiency commercially possible, the usual efficiency of standard equipment being of the order of 85 to 90 per cent. at full load and 75 per cent. at quarter load, as the only losses in addition to those of the transformer are the wattage used in the heater together with the small drop across the tube which we have seen is independent of load and is of the order of about 6 volts for tubes designed for an anode voltage below 50, and 12 to 16 for those with an anode voltage of 230 and upward. The heater consumption is from 2 to 3 watts per ampere output rating.

The standard commercial equipment caters for biphase output by means of a centre tapped secondary winding on the transformer, this tapping providing the negative output,

for three-phase by using a three-phase transformer or by direct connection to the mains of the three anodes either in a single tube or in three separate tubes. In the case of hexaphase, a three-phase transformer with its secondaries centre tapped is used, the tappings being joined to form the negative.

Power Factor.—The power factor of a rectifier is complicated in that it contains a component due to deformation of the current wave form and in phase with the voltage in addition to the lagging component brought about by the inductance of the transformer. The ultimate figure depends to some extent on the number of phases involved and the nature of the load; it is generally, however, of the order of from 0·8 to 0·9. The inphase component tends to correct any lagging power factor present on the same supply, and by connecting a rectifier across them the power factor of inductively loaded mains may be improved.

Where it is necessary for a rectifier to supply current that is continuous—as, for example, in the case of an arc lamp—either a three-phase or hexaphase rectifier will meet the conditions. A biphase rectifier has a point every half-cycle where the anode voltage falls below the value of the back E.M.F. of the valve and the current falls momentarily to zero. In this case a choke of sufficient inductance to ensure continuity of current must be included in the circuit.

As a definite limit has to be set on the peak current taken from any rectifying tube a capacity should never be joined directly across the output with the idea of smoothing the wave form, as the peak current will tend to reach very high values and bombardment of the cathode result. Further, the current through the load will be taken directly from the condenser and the regulation will be poor.

Where smoothing is required properly designed filters, calculated on the nature of the load and permissible peak current, should be employed.

LIGHTING

LIGHT and illumination are widely different terms in the sense that light may be described as the "Cause" and illumination as the "Effect."

Thus while a sufficiency of light may be provided in any given location, it does not follow that the area is correctly illuminated. Light can be (and often is) grossly wasted and misused, thus losing the major part of its usefulness, but light correctly used, and reflected or diffused, is converted into *illumination*.

As an example, the amount of *light* emitted by a given source, such as an electric lamp, may run into several hundred lumens, but if it is not effectively controlled by correctly designed reflecting equipment, the resulting *illumination* on the place it is required, i.e. the plane of work, may be extremely small and insufficient.

Glare.—Glare has been described as light out of place. It may be "direct" or "reflected," that is, direct from the light source to the eye (as caused by unshielded lamps in the line of vision), or reflected from an object (such as a highly polished machine surface). Both forms are capable of causing visual discomfort and a consequent loss of efficiency in work.

Care must be taken, therefore, when endeavouring to improve a lighting installation, not to rely solely on an increase in candle-power. Suitable reflecting equipment must be employed in order not only to prevent objectionable glare but also to ensure correct distribution of the light-rays to the best advantage.

SUGGESTED ILLUMINATION VALUES

	Ft.-cdls.		Ft.-cdls.
Good street lighting (minimum)	0·20–1·0	Lighting in factories, machine shops, etc.	7·0–10·0
Outside yards, etc	0·5–1·5	Engraving, Toolmaking, etc.	10·0–20·0
Corridors	0·6–1·5	General Offices, showrooms	10·0–15·0
Warehouses, auditoriums, etc.	1·5–3·0	Drawing Offices	20·0–30·0
General lighting in factories	2·0–5·0	Shop windows	25·0–40·0
General lighting in houses	4·0–7·0	Fine work such as testing and inspection	30·0–50·0
General lighting in workshops	5·0–8·0		

The modern electric lamp, both of the gas-filled and electric discharge types, owing to its high intrinsic brilliancy, will, unless installed with properly designed equipment, cause acute visual discomfort, and thereby nullify all the advantages of the increased intensity which its high efficiency provides.

The Measurement of Light.—Admitting the necessity of proper lighting in the interests of safety, health and efficiency, a means of measuring same and deciding on the various degrees required for different operations is essential.

The Lumen.—Light being a form of energy, it is important that the unit of energy should not be confused with the unit of intensity (candle-power). The " lumen " or unit of luminous flux may be considered as the unit of light energy in much the same way as the inch is the standard of rainfall over a certain area, as it embodies the area illuminated by a light source of definite intensity, and the degree to which such area is illuminated, namely, one square foot of surface to an intensity of one foot-candle.

Thus, a lamp giving one candle-power at a distance of one foot, providing an illumination of one foot-candle over an area of one square foot, is producing one lumen over that area. As such a light giving an equal intensity in all directions would produce a similar illumination all over the interior surface of a sphere of one foot radius (two feet diameter), it would illuminate 12·57 square feet, thus producing 12·57 lumens, which is therefore often stated as the equivalent of one candle-power.

This is clearly shown by Fig. 1, where an area of one square foot is indicated as removed from a sphere of one foot radius. Thus, a lamp may be rated in the terms of the lumens it produces :

$$\text{Lumens} = \text{foot-candles} \times \text{area in feet}$$

or

$$\text{Foot-candles} = \frac{\text{lumens}}{\text{area in square feet}}.$$

Efficiency.—The efficiency of a lamp is measured either (1) by considering the candles per watt or (2) the luminous output of lumens per watt expended.

The latter (or *lumens* per watt) method is more reliable and satisfactory, and is obtained by dividing the total lumens obtained from the lamp by the input in watts.

A table giving these values for all sizes and voltages of gas-filled lamps appears below.

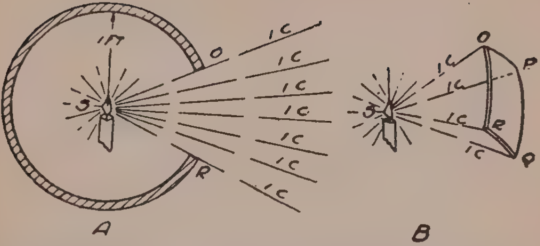


FIG. 1.—A pictorial explanation of the LUMEN. A square foot of the surface of a sphere one foot radius has one lumen of light flux if one candle-power is placed at the centre of the sphere.

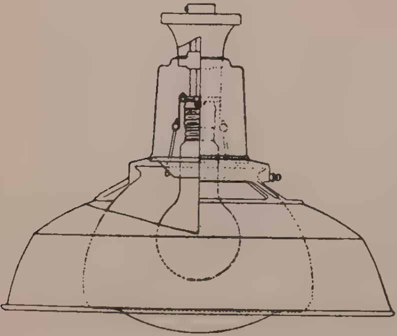


FIG. 2.—A dispersive type reflector suitable for factory use.

TABLE I

LUMENS OR QUANTITY OF LIGHT

Approximate rated Lumen Values of Gas-filled Lamps

Rated Watts.	Lumens.	
	100–130 Volts.	200–250 Volts.
15	140	118
25	240	215
40	470	345
60	790	610
75	1,060	820
100	1,500	1,210
150	—	2,030
200	—	2,900
300	—	4,720
500	—	8,470
750	—	13,610
1,000	—	19,100
1,500	—	30,300

Computing in Lumens.—The lumen method of calculating for illumination values is the easiest to apply as well as the most accurate, but it must be remembered that all the light from a lamp is not effective since some of it is absorbed by the reflector and certain other amounts may be absorbed by the walls and ceiling.

As an example, let us suppose a workshop 100 feet square is to be illuminated by means of 200-watt lamps in dispersive reflectors. The lamp gives approximately 2,900 lumens. If the reflector, ceiling and walls absorb 33 per cent., 67 per cent. or 1,943 lumens will be effective per unit. If an intensity of 10 ft.-cdls. is required, one lamp will serve $\frac{1940}{10} = 194$ sq. ft.

Utilization Efficiency.—If light is to be the productive factor (which it is capable of being) in any organization, it must be planned, and every factor capable of influencing its correct application must be given due consideration.

The first consideration is how to utilize the electrical energy consumed by the lamps; in other words, how to

obtain by suitable direction the maximum effect in light on the work per unit of current consumed by the lamps.

This factor naturally depends upon—

(1) the efficiency of the lamps in converting the electrical energy into light, and

(2) the efficiency of the reflecting equipment in converting the light into illumination.

The efficiency of the lamps is a factor which is fixed (see Table I) and there are only two ways to assure that this efficiency is maintained. The first is to see that the lamps are run at the voltage for which they are rated, bearing in mind that a reduction in voltage of 10 per cent. results in a decrease in the candle-power of the lamp of 33 per cent.

It is therefore false economy to contrive to save in the cost of lamps or prolong their life by running them on a voltage lower than that for which they are rated.

Table II below shows the relative value of lamps in terms of their luminous output, when compared with their relative capital cost and relative cost of current consumed. This novel comparison should prove of great value to those interested in obtaining maximum economic efficiency from their lighting installation.

TABLE II

RELATIVE LAMP COST AND EFFICIENCY

Based on 230-volt rating (B.S.S. 161–1934)

Watts.	Lamp Cost relative.	Lumens.* Total.	Lamp Cost relative per Lumen.	Current Cost relative per Lumen.	100-v. Lumens. Total.
60-w. Pearl	1·0	595	3·75	1·93	760
100-w. ,,	1·43	1,180	3·69	1·62	1,380
150-w. Clear	2·86	1,945	3·28	1·48	2,160
200-w. ,,	4·28	2,730	3·5	1·4	3,040
300-w. ,,	5·71	4,380	2·91	1·31	4,830
500-w. ,,	7·15	7,920	2·02	1·21	8,900
1,000-w. ,,	9·14	17,900	1·14	1·068	19,800
1,500-w. ,,	12·85	28,700	1·0	1·0	31,300

* The lumen is the unit of quantity of light.

For Coiled-Coil Lamps increase lumen values in Columns 3 and 6 as follows: 60 watt—15 per cent. 100 watt—10 per cent.

From this table it will be seen that by using 60-watt lamps instead of 1,500 watt, the lamps cost four times as much per lumen of output and the current they consume costs twice as much.

Also it will be noted from the last column that considerably more light is given by 100-v. lamps.

The next factor is known as the utilization efficiency and denotes the amount of light delivered on the work—in foot-candles—compared with that produced by the lamp—in lumens.

If all the light from the lamp reached the work directly without reflection, we should have a utilization efficiency factor of 100 per cent., but much of the light goes upwards and sideways and consequently has to be reflected on to the work. There is always some loss when light is reflected, and, as previously mentioned, further losses will occur due to absorption by walls and ceiling. Allowance must also be made for a depreciation factor, due to dirt and dust accumulation, ageing of lamps, etc.

The coefficient of utilization naturally varies according to the surroundings, and the type of reflecting equipment used and a brief survey of the main types of reflection will not be out of place.

Regular Reflection.—This may be described briefly as that proceeding from glass, mirrored glass, or polished metal surfaces. Naturally such lighting has to be employed with caution, because the light rays are reflected at a definite angle, and are therefore liable to cause glare, in addition to producing hard shadows. Reflecting surfaces of this character of course have their uses, such as flood-lighting, spot-lighting and occasionally as supplementary units to general lighting by diffuse reflection.

Diffuse Reflection.—For general indoor industrial lighting, diffuse surfaces are greatly preferable, as they afford a soft light free from glare or hard shadows. A high-quality vitreous enamelled surface provides ideal diffused reflection, does not deteriorate or scratch, has a longer life and presents a better appearance over a longer period of time, than other surfaces. Initial efficiency can also be maintained practically indefinitely by periodical cleaning.

Importance of Manufacturing Process.—Although vitreous enamelled reflectors have been generally accepted as the most practical for indoor and outdoor industrial uses, the quality and efficiency of the surface combined with the correct optical contour of the reflector is of the utmost importance.

Thus the quality and colour of the enamel and the evenness of the surface make an appreciable difference in the

lasting qualities and reflecting efficiency, considerably affecting the value of the reflector as a piece of lighting apparatus.

A cheap vitreous enamel surface will have a very low reflection factor as compared with a scientifically designed reflector having a high quality reflecting surface, and although there may not be a great difference in appearance, actual light-meter tests will show a wide variation in actual lighting efficiency.

For instance, one well-known reflector manufacturer specializing in scientifically designed reflector equipment claims a reflection factor from the special surface employed in their products of between 80 and 85 per cent.—a satisfactorily high figure and one which is considerably in advance of that attainable with old types of enamelled surface.

Economics.—The economics of good lighting must be considered under two headings:

(*a*) The economics of installation.

(*b*) The economics of maintenance.

(*a*) *The Economics of Installation.*—Often a common mistake is made in the direction of making inadequate provision for the lighting load, owing to this having been computed on some arbitrary basis (e.g. lighting load taken as a percentage of power load), regardless of the type of work to be done. Such an error may prove costly.

Either the supply authority's cables, or those within the factory, or the switchgear, or all three may prove to be inadequate for the lighting load shown to be necessary. To allow for the constant upward trend of lighting, it is recommended that all cables be capable of carrying a 50 per cent. increase in load at maintained lamp voltage.

Again, supposing an adequate provision has been made in the matter of lighting load and that due regard has been paid to the amount of light necessary to the work carried out, a serious loss can occur through selection of unsuitable or inefficient reflecting equipment.

Previous reference has been made to this important point, but it may be amplified by stating that the best is cheapest in the long run, and it is eminently worth while at the outset to have the lighting installation planned on scientific lines. Poor reflectors usually mean a larger number of points resulting in higher wiring costs, more lamps to buy and replace, and a greater current consumption.

(*b*) *The Economics of Maintenance.*—It is false economy to use old lamps in a lighting installation, because the cost of

the current consumed by a lamp exceeds the cost of the lamp many times over.

For general industrial application we need consider only direct and semi-direct lighting. The accepted type of direct lighting is known as general lighting, a term implying that the general illumination of the area takes place from overhead as apart from a system of local lights.

Localized general lighting can be taken to mean the lighting system whereby general lighting is located with due regard to the lay-out of the plant, machinery, benches, workpeople, etc.

Considerable reluctance is often shown towards relamping, the reason being that the purchase of the new lamps is at once appreciable as an item of expenditure, but a lamp ceases to be efficient when its luminous output depreciates. This depreciation, in terms of wasted current, far outweighs the saving effected in lamp replacement.

The regular cleaning of lamps and reflectors is a vital factor in the economy of maintaining the installation. The efficiency of an installation can be lowered by over 70 per cent. by the accumulation of dust on the lamps and reflectors alone.

Simple cleaning charts can be employed to ensure methodical and frequent cleaning by an operative detailed for the purpose.

The depreciation in reflection factor of walls and ceilings owing to discoloration and dirt, is to a large extent inevitable, and the only remedy is repainting at intervals. With modern reflecting equipment, however, the reflecting power of walls and ceilings is not so important a factor as would be the case where bare lamps or inefficient obsolete conical shades are used, because the optical contour of the scientifically designed reflector virtually covers the lamp and redirects the light-rays without the need of further external reflection aids.

Systems of Lighting.—There are four main systems by which artificial lighting can be applied to the needs of the worker.

1. Direct lighting, in which not less than 90 per cent. of the total flux of the fitting is in the *lower* hemisphere.
2. Semi-direct lighting, giving more than 60 per cent. and less than 90 per cent. in the *lower* hemisphere.
3. Semi-indirect lighting, giving more than 60 per cent. and less than 90 per cent. in the *upper* hemisphere.
4. Indirect lighting, giving not less than 90 per cent. of the total flux of the fitting in the *upper* hemisphere.

Supplementary lighting implies the raising to a higher value of illumination than the surrounding area, some particular point upon which work of special importance is being done.

The general character of the work must determine the type and standard of the illumination system installed, but it should be mentioned that, in general, there should never be great difference of light value in any one area in which work is being performed.

Thus, it is bad practice to have a very low general illumination supplemented by very high-power reflectors concentrating the light upon the actual press, bench or machine where the work is being done. The strain unconsciously imposed upon the eyes of the operatives in looking from bright to dark areas, and back again, is a frequent source of fatigue and accidents.

Diffused Lighting.—One of the essential points in the design of a reflector is that it shall, when used with the lamp for which it is designed, have a surface brightness well below the values prescribed as being harmful to the eyes. It follows therefore that the use of lamps of greater power than suitable for the reflector will negative this precaution. Similarly, the use of small lamps on large reflectors upsets calculations of light focus and distribution.

In a correctly designed reflector with a high quality vitreous enamelled reflecting surface, a considerable degree of diffusion is obtained which is sufficient for some locations. Many classes of work, however, call for a much greater degree of diffusion, and in these cases fittings of the type illustrated in Fig. 2 (the Benjamin glassteel diffuser) are ideal.

This fitting consists of a glass diffusing bowl which completely surrounds the lamp, and therefore supplies a large area of considerably lower initial brightness than the lamp itself.

In order, however, to obtain a high efficiency redirection of light into the useful working zone (60° either side of the vertical), a vitreous enamelled steel reflector is arranged round the diffusing globe.

Apertures in the top of this steel reflector permit a certain amount of light to pass upwards and thus avoid the depressing effect of gloomy overheads.

By the combination of this reflector and the diffuser bowl into one unit, a light of high efficiency is obtained, 70 per

cent. of it falling within the useful zone, but at the same time the light is completely diffused and all hard shadows upon the work are eliminated.

Artificial Daylight.—The standard gas-filled electric lamp has a preponderance of red and yellow in its spectrum, and in certain specialized industrial operations this excess is a disadvantage. Some form of correction is therefore necessary so as to obtain a closer approximation to natural daylight, and several methods have been introduced from time to time, claiming various degrees of correction.

In one case use is made of lamps whose bulbs are of blue glass (sometimes known as daylight lamps); in a second case the light from the lamp falls in part directly on to the work and is in part reflected from a specially coloured service; in a third case, no direct light is allowed to fall upon the work, but entire reflection from a coloured surface takes place.

Finally, and possibly the most satisfactory, is the system by which the light from a standard electric lamp passes through filter screens of specially prepared glass affixed to the reflecting unit.

Naturally with corrected lighting, a greater absorption factor is apparent, and therefore somewhat higher wattages must be employed to get satisfactory results. On the other hand, the greatly increased visual acuity afforded by (to say nothing of the restful nature of) corrected light, allows of lower intensities than would be necessary with ordinary electric lighting.

Electric Discharge Lighting.—With its output of from 45 lumens per watt in normal operation (being approximately up to two and a half times the efficiency of the gas-filled tungsten lamp), the electric discharge lamp has undoubted advantages, particularly in replacing inadequate lighting installations where present wiring is already loaded to capacity.

Basically, this new lamp consists of a mercury-arc source of light, provided with two glass tubular bulbs, one within the other, the inner bulb or arc tube having a main electrode in each end, between which the mercury arc flows when the lamp is in normal operation. The outer tube provides protection and support, and being at low pressure, acts as an insulator conserving the heat generated by the lamp, for completely vaporizing the mercury.

There is an almost entire absence of red and yellow rays

in the spectrum of the electric discharge lamp, and therefore in colour and effect it is widely different from the standard electric lamp.

Actually, the majority of the light produced is radiated in the yellow-green, with some blue-green and green parts of the spectrum, near the eyes' peak of seeing sensitivity.

Therefore, while the latter advantage provides greater sharpness of vision in those industries where the working, handling, inspection and assembly of minerals, metals, etc., are involved, electric discharge lighting is not recommended where accurate appreciation of all colours is required.

The stroboscopic effect common to arc sources is noticeable with high-speed rotary or reciprocating machinery, giving an effect of apparent slowing-up or flicker, due to the luminosity of the discharge being extinguished one hundred times a second on a 50-cycle supply. In such cases the connection of alternate lamps to the three phases entirely obliterates the stroboscopic effect.

The question of the time lag between switching on and full efficiency, which is a peculiarity of these lamps, is sometimes considered a disadvantage, but this has been considerably minimized by recent technical improvements in the manufacture of the lamps, resulting in a material reduction in the time taken for the attainment of full brilliance, or re-attainment after extinguishing.

It will be appreciated therefore that most of the early drawbacks to this form of lighting for industrial application have been overcome, and trials and experiments over a wide range of industries have proved beyond doubt its many advantages in many different locations.

In common with all arc sources, the electric discharge lamp requires the use of a choke in the circuit to limit the current and to prevent the arc "building up." A separate choke is necessary for each lighting point and can be mounted near each lamp. To compensate for the low power-factor of the lamp with choke, condensers can be fitted if increased power-factor correction is necessary.

Finally, electric discharge lighting is suitable only on alternating current supply, and again the importance of correctly designed reflecting equipment must be stressed.

Planning the Installation.—The same problem in illumination rarely occurs more than once. There are a number of important considerations common to many installations which must be borne in mind when deciding on an illumina-

tion scheme. Class of work carried on, type of machines used, surroundings and architectural details are all contributory factors to the success or otherwise of an installation, and while the well-known manufacturers of lighting equipment publish very full data which is of considerable help to the works engineer in planning a straightforward scheme, it is always advisable to utilize expert advice before coming to a final decision.

Most of these equipment manufacturers are fully organized to give the fullest possible assistance and technical advice on all artificial lighting matters, without obligation or cost, and their help should be freely sought, in preference to installing cheap equipment in a haphazard manner.

Recent Advances in Electric Discharge Lamps.—The number of types of discharge lamp has increased recently, and many types of applications are now catered for. The following table shows the present range of Mercra Electric Discharge Lamps.

Lamp. Watts.	Lumen Output.	Efficiency Lumens per Watt.	Cap.	Overall Length.	Overall Diameter.
400	18,000	45	G.E.S.	325 mm.	50 mm.
250	9,000	36	G.E.S.	290 mm.	50 mm.
150	4,800	32	E.S.	230 mm.	43 mm.
125	5,000	40	3-pin bayonet	178 mm.	90 mm.
80	3,040	48	do.	160 mm.	80 mm.

Of the above lamps the 400-watt is the standard source for the most effective road lighting. On some road-lighting schemes, however, the 250-watt size is used. The 125- and 80-watt sizes are of great value for side-street lighting. For applications other than road lighting, including the lighting of factories, garages, workshops and outside yards, the 250-watt is the favourite size and the 125-watt and 80-watt sizes are also used. The 400-watt size is occasionally used where it is necessary to floodlight a large area.

Considerable improvements in road lighting can be brought about if the linear light source of the mercury-vapour discharge lamp is arranged in a horizontal plane. This can be done, using standard lamps, by arranging within the lantern a magnetic field, so positioned in space that the arc which normally flows upwards by means of convection currents,

is depressed back into the centre of the tube. It is not possible to operate the standard lamps conveniently in a horizontal position without magnetic control, and recently a lamp has been introduced of a slightly lower efficiency which enables this to be done. The rating and dimensions of this lamp are as shown under.

Lamp. Watts.	Lumen Output.	Efficiency in Lumens per Watt.	Cap.	Overall Length.	Overall Diameter.
400	16,000	40	Goliath Ediswan Screw	325 mm.	50 mm.

A very noteworthy improvement recently made available to the public concerns the modification of the colour quality of the mercury-vapour discharge lamp, and a lamp is now available in which, compared with the mercury-vapour lamp, extreme violet colour has been suppressed, the middle blue has been enhanced, and a considerable percentage of red light has been added. The table below compares the new Mercra Fluorescent Lamp with the standard mercury-vapour lamp.

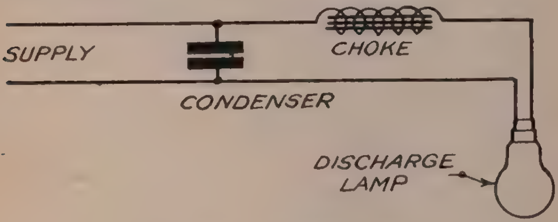
Lamp.	Lumen Output.	Per cent Red.	Overall Diameter.	Overall Length.
400-watt Fluorescent	15,200	5–6	165 mm. max.	330 mm.
400-watt Standard .	*18,000*	*1*	*50 mm.*	*325 mm.*

As this lamp is so new, a brief description will be of interest. The modified spectral output is obtained by the use of special fluorescing powders. These are placed on the inner surface of the outer jacket. It will be noticed from the dimensions that even though the wattage remains the same, the outer bulb is of much larger diameter in the case of the fluorescent lamp. This is because the powders that are used are sensitive to temperature and show both initial decrease and continued fall off of efficiency during life, if they operate at too high a temperature. The shape of the bulb, in addition to its large diameter, is also designed to secure, as much as possible, an even distribution temperature, and is best described as a pear-shape.

While the colour is considerably improved, the lamp is

by no means one that gives an output corresponding to true daylight. It is, however, a very considerable improvement, as regards colour, over the standard mercury lamp, and will be of considerable use in many industrial applications. While it will perhaps be used in certain street-lighting installations, it is quite clear from its lower efficiency and from its design that it is not intended for extensive street-lighting use. The fluorescent powder acts, to some extent, as a pearl jacket and diffuses the light source, and taking into consideration the large diameter of the jacket, optical redirection from such sources is difficult.

In considering the colour of the Mercra Fluorescent Lamp, it should be noted that on a comparative scale, percentage red in an ordinary mercury lamp is 1 per cent., in sunlight 15 per cent. and in the tungsten-filament lamp approximately 25 per cent. This means that although the new lamp cannot be used for colour matching, it can be used for colour discrimination. Factory operatives will probably prefer the colour as being the more pleasing light under which to work.



Connections for Discharge Lamp.

SHOP-WINDOW LIGHTING

Shop-window lighting has reached a very high stage of perfection and the essential principle is that the light is directed in such a way as to display the goods to the best advantage, the most important point being that the source of light must be absolutely invisible from outside the window.

Intensity Required.—The intensity of light required is controlled to a large extent by the contrasting requirements as regards the outside of the shop (i.e. the pavement). By this is meant that the efficacy of the window lighting is judged by its attraction compared with the outside conditions. In main streets, therefore, it will be necessary to have a very high intensity of light in order to compete with the high standard now used in main thoroughfares.

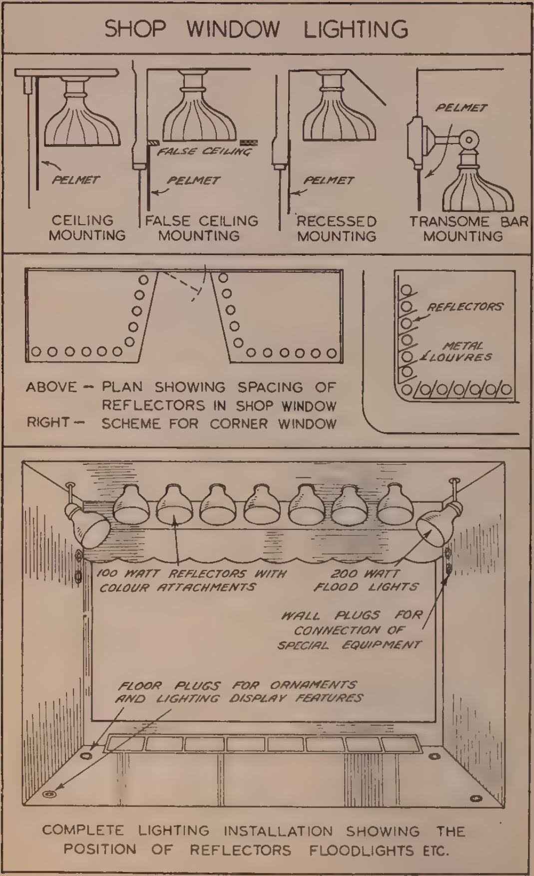
As a contrast to this a shop in a side street which is not so well lighted will be quite as effective if only half to two-thirds the proportionate amount of light is used.

The normal and simplest method is to mount the reflectors on the ceiling immediately behind the window and, if they are not naturally hidden by the shopfront, a pelmet should be arranged in order to prevent the lamps being seen from outside.

An alternative method is to mount the reflectors above the ceiling or use a false ceiling with holes to take the reflectors.

As in most cases *front* lighting gives the best results, reflectors are normally at an angle and can usually be obtained either vertical or with various angles for shallow and deep windows.

Additional Lights and Effects.—Even with the best designed system of reflectors, certain types of window displays have dark places, or alternatively there are certain items which require "picking-out." For this purpose spot and projector lamps should be used, and from the wiring point of view a really adequate supply of plug points should be installed both in the floor of the window and round the walls near the ceiling in order to supply spotlights and extra reflectors. These plugs and sockets give a flexibility which is essential for windows in which the display varies.


SHOP WINDOW LIGHTING
PELMET
CEILING MOUNTING
FALSE CEILING
PELMET
FALSE CEILING MOUNTING
PELMET
RECESSED MOUNTING
PELMET
TRANSOME BAR MOUNTING
REFLECTORS
METAL LOUVRES
ABOVE — PLAN SHOWING SPACING OF REFLECTORS IN SHOP WINDOW
RIGHT — SCHEME FOR CORNER WINDOW
100 WATT REFLECTORS WITH COLOUR ATTACHMENTS
200 WATT FLOOD LIGHTS
WALL PLUGS FOR CONNECTION OF SPECIAL EQUIPMENT
FLOOR PLUGS FOR ORNAMENTS AND LIGHTING DISPLAY FEATURES
COMPLETE LIGHTING INSTALLATION SHOWING THE POSITION OF REFLECTORS FLOODLIGHTS ETC.

Colour Lighting.—Colour lighting has been found most attractive and the most satisfactory method of obtaining colour effects is by the use of screens clipped over the reflectors. In all cases it is advisable to increase the wattage where colour is used to any extent. Movable spotlights are ideal for colour purposes.

Mercury Discharge Lighting.—The particular colour of mercury lamps and their higher efficiency has brought them into use for shop window lighting. In this connection it should be noted that the ordinary gas-filled metal-filament lamp has far too much *red*, whereas the mercury discharge lamp has practically no red at all. It has therefore been found that a combination of the mercury discharge lamp with the ordinary gas-filled lamp gives an effect quite closely approximating to daylight and is both efficient and attractive.

The new small-size mercury lamps have opened up a new technique and it has been found that an ideal combination is one 80-watt mercury discharge lamp placed in between two 150-watt gas-filled lamps. With this arrangement it is preferable to have an oblong-type reflector with the three lamps mounted therein. As the colour of the display affects the efficacy of the division of lamps it is quite simple to experiment by reducing the size of the gas-filled lamps until the ideal effect is obtained.

Bottom Lighting.—For certain merchandise, particularly glassware, bottom lighting is very effective, and for this purpose properly shaded footlights should be used.

Lamp Size and Spacing.—The following table gives typical arrangements for three intensities of light and may be used as a general guide for the setting out of general shop-window lighting.

TABLE

Lamp Size and Reflector Spacing

Window. Height (ft.)	Window. Depth (ft.)	District Brightness.*	Reflector Spacing, inches. 60w.	75w.	100w.	150w.	200w.
6	3	Low	21	—	—	—	—
		Medium	10	14	20	—	—
		High	—	—	13	20	—
	5	Low	18	24	—	—	—
		Medium	—	12	17	—	—
		High	—	—	12	18	—
8	4	Low	16	21	—	—	—
		Medium	—	10	15	23	—
		High	—	—	10	15	22
	6	Low	14	18	—	—	—
		Medium	—	—	14	21	—
		High	—	—	2 rows 18	14	20
10	5	Low	13	17	24	—	—
		Medium	—	—	12	18	—
		High	—	—	2 rows 16	13	18
	8	Low	11	14	21	—	—
		Medium	—	—	10	16	23
		High	—	—	2 rows 14	11	15
12	6	Low	10	14	20	—	—
		Medium	—	—	10	15	22
		High	—	—	2 rows 14	11	15
	8	Low	10	13	19	—	—
		Medium	—	—	2 rows 18	14	20
		High	—	—	2 rows 13	10	14
	12	Low	—	11	16	24	—
		Medium	—	—	2 rows 15	12	17
		High	—	—	2 rows 10	2 rows 16	2 rows 23

* District brightness is assessed as :—

"Low" . . . In main streets of small towns.
"Medium" . . . In main streets of large towns.
"High" . . . In central shopping areas of large towns.

REMOTE STREET LIGHTING AND OFF-PEAK LOAD CONTROL

G.E.C. SYSTEM

THE system of remote control switching, which has been developed by The General Electric Co., Ltd., employs alternating currents of musical frequencies between 300 and 800 cycles per second, superimposed on the existing supply network. The signal current is sent out at a pre-determined frequency and flows throughout the network, or section of the network under control, to operate receiving relays connected to the low voltage mains and mechanically tuned to respond to a particular frequency.

The frequency supplies are obtained from a variable speed alternator and are injected into the system mains by means of injection transformers connected in either the high-tension or low-tension feeders, depending upon the scheme of control. The G.E.C. system is equally applicable to A.C. and D.C.

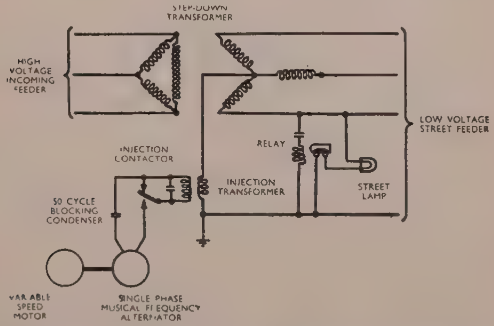


FIG. 1.—Diagram of Connections G.E.C. Centralised Control System.

Showing the Method of Low-tension Injection on the Secondary Side of the Power Transformer.

networks. Operation is largely independent of the strength or duration of the signalling current.

Two general schemes of injection are available, one for use on the low-tension side of the network power transformers (400/230 volts) and one for installation on the high-tension side, which may operate at any voltage between 3,300 and 33,000 volts. The latter scheme can further be subdivided into a series and a parallel method with the injection transformers connected respectively in series with the outgoing feeders and across the main busbars through coupling condensers. With the low-tension scheme, the secondary of the injection transformer is connected between the neutral point and the neutral wire of the main transformer.

The sequence of operations is as follows :—

(1) The motor starts, and when running at the correct speed for a particular signal frequency, the injection contactor closes. (2) With the injection contactors closed, the alternator is connected to the primary of the injection transformers. (3) The output voltage of the alternator is then adjusted to the value required. (4) The relays on the system operate (this takes about 5 seconds). (5) A master relay, mounted on the control panel, operates when all the other relays have operated and shuts down the equipment ready for the next operation.

The control system is so designed that further signals (frequencies) can be added at any time without any alterations or additions to the receiving relays already installed.

ACTADIS SYSTEM

In the Actadis ripple control system developed by Messrs. Measurement, Ltd., loads are controlled by injecting a superimposed signal into the distribution system from a transmitter in the central supply station, the superimposed signal being an alternating current with a different frequency from that of the main supply and having the same number of phases as the load (see Fig. 2).

The power requirements of the high frequency ripple alternator vary from about 10-30 kVA on a small system to about 100-150 kVA on a large system. Production of the various signal frequencies is obtained by varying the speed of the alternator, and the voltage of the ripple is controlled by a servo-motor-operated rheostat controlling the excitation of

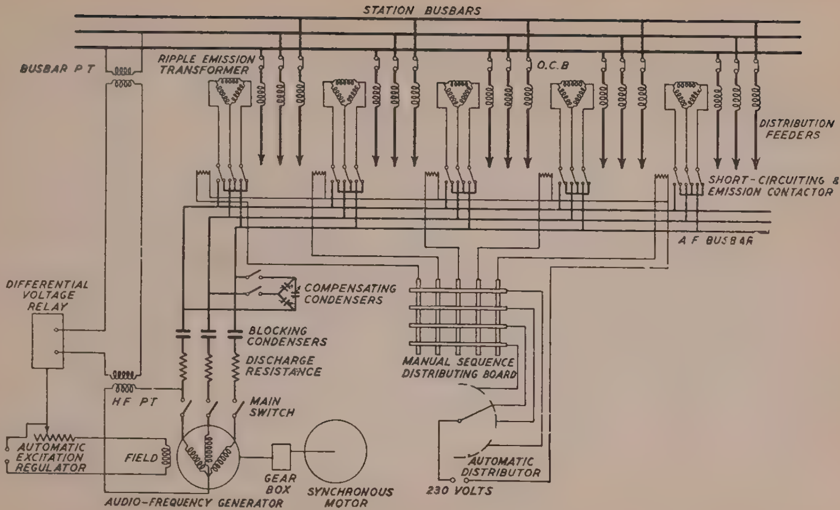


FIG. 2.—Diagrammatic Arrangement of Actadis Transmitter at Central Station.

the generator. With a synchronous-motor drive, the frequency of the ripple requires no regulation.

The Actadis system of centralized control provides for the installation of one emission transformer for each feeder, or, in small undertakings, for each busbar. When no signal is being sent out, each transformer is disconnected on the primary side by a contactor. Suitable contactor gear automatically controls the compensating power-factor correction condensers (connected across the phases of the alternator), and the various auxiliary circuits.

D.C. BIAS SYSTEM

This system, devised by Standard Telephones & Cables, Ltd., involves the use of one transmitter to each substation. Centralization of control may be achieved from each substation or the substations may be linked in addition by pilot wires connected to a master control unit at a central control station. A D.C. bias applied to the A.C. distributing cables constitutes the form of superimposed signal used.

The D.C. bias is applied to the A.C. system between phase and neutral at each substation ; the bias for a few seconds displaces the phase-to-neutral voltage towards positive or negative, giving " on " or " off " signals.

With a bias of 6 volts it is possible, by means of a specially designed transformer type of choke, for a relay to respond only to this D.C. bias. (This holds when the voltage employed for the bias is 1 volt or less, while the A.C. voltages are of the normal values of 200–240 phase to neutral.) By using 6 volts as the energizing bias and relays that will operate at 4 volts, ample margin for robust operation is assured.

The equipment at the substation (Fig. 3) includes a 6-volt battery connected in series with the neutral feeder and the star point of a low-tension transformer. A change-over switch enables D.C. bias to be sent in either direction, whilst a heavy-duty resistance of 0·1 ohm, normally short-circuited by a contact B, serves to prevent the circuit from being opened while the mechanically interlocked non-simultaneous contactors A and B operate.

Provided impulses are " poled " to agree with the street-lighting condition, they can be sent as often as desired. Each of the remaining services is selected by means of two impulses time-spaced by a distinctive interval, each service using a different interval of time.

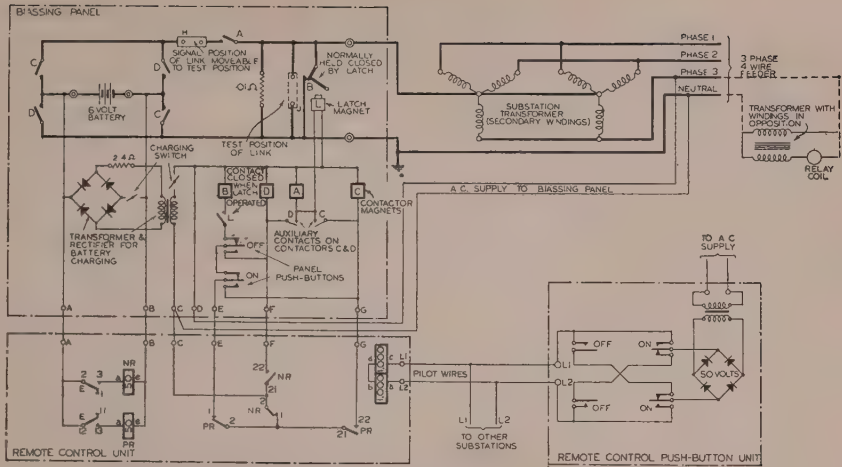


Fig. 3.—Schematic Circuit of D.C. Biasing Panel with Remote Control.

(*Standard Telephones & Cables, Ltd.*)

SORDOVISO CASCADE CONTROL

The main principles of Sordoviso Cascade Control for street lighting will be seen from Fig. 4, which shows a simple series system where each section is automatically switched on by the preceding one. The master switch operates the first section through the relay No. 1. This switches the

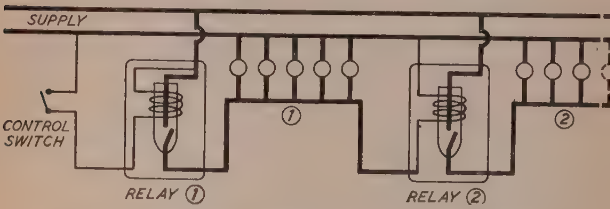


FIG. 4.—Sordoviso Cascade Control for Street Lighting.

lamps in section 1 and relay No. 2 is then automatically energized thus connecting the lamps in section 2, and so on. Each subsequent group can be connected to a different phase.

A development of this system is the use of delay switches in order to ensure a time lag between the switching on of the different sections.

Another variation is the use of twin contactors for controlling the two sides of a street.

ACCUMULATORS

Lead Acid Accumulators

The active components of lead-acid cells are the lead peroxide, PbO_2, of the positive plates (brown), the spongy lead, Pb, of the negative plates (grey) and the sulphuric acid, H_2SO_4, of the electrolyte. During discharge there is a partial reduction of the positive-plate material with oxidation of the negative-plate material and combination of the product in each case with sulphuric acid. The result is a transformation of part of the material of both plates into lead sulphate, $PbSO_4$, accompanied by a lowering in concentration of the electrolyte. During recharge this process is reversed and restores the original system.

The fundamental chemical action is represented by:

$$\underset{\text{Positive.}}{PbO_2} + \underset{\text{Electrolyte.}}{2H_2SO_4} + \underset{\text{Negative.}}{Pb} \underset{\text{Charge.}}{\overset{\text{Discharge.}}{\rightleftharpoons}} \underset{\text{Positive.}}{PbSO_4} + \underset{\text{Electrolyte.}}{2H_2O} + \underset{\text{Negative.}}{PbSO_4}$$

Large stationary batteries employ Planté positive plates in which the lead peroxide is "formed" by a chemical and electrolytic process on the laminated surfaces of pure lead plates. The negative plates used in conjunction are usually of the "box" type and consist of coarse lead grids faced on both sides with thin perforated sheet lead. These hold the spongy lead which is produced by filling with a lead oxide-sulphuric acid paste and reducing electrolytically. These batteries are assembled in glass jars or lead-lined wood boxes. The plates are arranged alternately positive and negative (both outside plates being negative), and separated by acid-resisting spacers which are frequently glass tubes. Each group of positive plates are welded to a bar and similarly the negatives to give positive and negative connections for each cell. The boxes are large and the working strength of the electrolyte is fairly low (specific gravity 1·200 to 1·230), which assists in prolonging the life of the plates.

Other types of batteries as are used for car-starting and lighting employ pasted plates. These are developed from Faure's plates and the active material is held in antimonial lead grids. The grids are pasted with lead oxide-sulphuric acid pastes which are afterwards converted electrolytically to the required active materials. Plate thicknesses depend upon the work for which they are designed and vary from about 1·5 mm. for aeroplane batteries to about 2 mm. for car-starting and about 5 mm. for electric traction. Generally, the thinner a plate the less robust it is in service, but the greater the output it will give when discharged at high rates.

Such batteries are assembled in ebonite or composition containers either as monobloc units having multiple cell compartments or as individual cells housed in crates. The separators have about the same thickness as the plates and usually consist of sheets of treated wood or of porous or perforated ebonite. For special heavy duty purposes such as electric traction, various devices are employed to assist in retaining the paste in the positive grid. The acid space is always limited and the working strength of the electrolyte is consequently high (specific gravity approximately 1·280).

Charge.—Manufacturer's instructions must be adhered to when charging batteries, and it is only possible to consider the important points to be observed. Very pure acid and distilled water must be used in this connection.

Dry and uncharged batteries have to be given a first charge in which the strength of acid for filling, time of soaking before commencing charge and charging rate are always carefully specified. During the first charge a fault in any cell is indicated by backwardness in reaching the gassing stage and by overheating. The fully charged readings and strength of electrolyte for final adjustment vary with different types, but first charge is never complete until the voltage (on charge) is over 2·45 volts per cell and all the plates are gassing.

Subsequent charges on a battery after use are known as recharges and it is essential not to exceed the specified charge rate. Generally, the rate should be sufficient to charge the battery fully in about 15 hours. Charging is complete when voltage and specific gravity readings have remained constant for two hours, and by then the condition has become as at the end of first charge. As the ampere hour efficiency is about 90 per cent., the charging rate can be deduced by allowing an input over the 15 hours of 120 per cent. of the ampere hours discharged.

Maintenance.—Batteries and vessels used in connection therewith should be kept scrupulously clean, as impurities inside and moisture outside cause rapid self-discharge and deterioration. Vent plugs must be free from obstruction to avoid internal gas pressure and naked lights or sparking near batteries will ignite the evolved gases, causing violent explosions.

If any acid is accidentally spilt from a cell the level in that cell may be restored by adding acid of the same concentration. For normal topping up only distilled water can be used and the electrolyte level should never be allowed to fall below the tops of the plates.

Alkaline Cells

The alkaline cell is a cell having a positive plate mainly consisting of nickel hydrate, Ni(OH), mixed with other ingredients, the most important being a specially treated graphite, and negative plate of cadmium and iron oxides, CdO and FeO. The electrolyte consists of a solution of potassium hydrate (KOH) in distilled water to a specific gravity of 1·190. The chemical reactions taking place in the alkaline cell are very involved, but the main features are that, when current passes, the electrolyte is split up into its component parts, K′ and OH′, which reaction results in the following changes:

Charge—Positive oxidized, Negative reduced.
Discharged—Positive reduced, Negative oxidized.

"Nife" Accumulators

This type of cell is very sturdy and will stand extremely high rates of discharge even to short circuit without buckling the plates.

When discharging at the one hour rate it will give 100 per cent. of its rated capacity.

Although it is practically "foolproof" the following points should be observed.

Unlike the lead-acid cell, the average voltage of an alkaline cell when discharged at the normal rate is approximately 1·2. The number of cells employed for a given voltage battery, however, varies somewhat with the application, and the makers should be consulted.

Charge.

Owing to the difference in characteristics alkaline cells should never be charged in the same circuit with lead-acid cells, as such a practice would be detrimental to both types of accumulators.

When discharged alkaline cells are put on charge at normal rate (i.e. the 6 hour rate of charge) the initial voltage is about 1·4 per cell and this rises during the first half hour to about 1·5 and thereafter more gradually until after three hours another rapid rise takes place, so that at the end of the fifth hour the top voltage of about 1·75/1·8 is reached. The charge must then be carried on at the full rate for a further hour.

N.B. Specific Gravity readings give no indication whatever of the state of charge of an alkaline accumulator.

Maintenance.—The first and foremost fact to be borne in mind in dealing with this type of cell is that any contact

with sulphuric acid will completely ruin the battery. No utensils which have been used in connection with lead acid batteries should be permitted anywhere near an alkaline cell.

In order to preserve the steel plates the specific gravity of the elctrolyte must be kept between the safe limits of 1·19 to 1·16. After about two years (depending on the nature of the service) the electrolyte should be completely renewed owing to the fact that it absorbs impurities from the atmosphere. Always use distilled water for topping up the cells to make good the evaporation which takes place. Never top up with electrolyte unless instructed by the makers, or to replace accidental spillage. Keep exterior of cells dry and clean and lightly smear with vaseline.

Battery Erection.—The erection of storage batteries is very important. After deciding upon the place where the battery is to be housed, a lay-out of the proposed arrangement of the stands should be made. Care must be taken to arrange the stands so as to leave maximum room between the rows for gangways. If room permits, it is well to put the battery on single-tier stands, because they greatly facilitate inspection, cleaning, and so on. Many times, however, double-tier stands have to be used, and occasionally step-stands are used. All wooden stands are insulated from earth by glass insulators.

Having arranged and erected the stands, the glass boxes should be unpacked, thoroughly cleaned, and examined as to their soundness. A gentle tap will tell if a box is cracked or defective. The boxes should now be placed in position on the stands, carefully spaced and aligned. Each box is placed upon porcelain insulators. Between the bottom of the box and the insulator a washer is inserted to prevent the slippery glass from sliding on the polished porcelain surface. Several washers may be used so as to get all the tops of the boxes level.

The plates are now inserted into the boxes. It will be noticed when the plates are unpacked that the groups, complete with separators, are held together by cord. When the groups are inserted in the boxes the cords are cut and the end springs are fixed in position. When inserting the groups, care must be taken so as to have positive and negative straps in the correct position for connecting up, either by means of bolts or burnt connections in the case of a large battery.

The cells after being erected and connected up should not be filled with electrolyte until arrangements have been made for the first charge.

BATTERY CHARGING

Many different types of battery chargers are now marketed. These comprise valve rectifiers, metal rectifiers, commutating rectifiers, motor generators, rotary transformers, lamp boards, resistance boards and mercury arc rectifiers. In addition, specialized battery chargers operating on the constant potential system are available, these chargers also involving the use of motor generators, commutating rectifiers or rotary transformers.

These different types of battery chargers can in principle be reduced to two methods, namely, the constant current method and the constant potential or constant voltage method.

Any consideration given to battery charging should be associated with the type of charging method to be adopted, and to enable the difference between the two methods and the characteristics of the various types of plant available to be appreciated, it is necessary firstly to consider the fundamental principles of battery charging as exemplified in the behaviour of the battery itself during charging and discharging, and of the considerations involved during the process of recharging batteries for commercial purposes.

The effect of passing a current into a battery is to cause a chemical change to take place. When a battery is charged the electrical energy is converted into chemical energy. A certain loss occurs in this transformation, this loss being indicated by the efficiency of the battery in the same way as with all other classes of electrical machinery.

Any battery consists of two sets of plates—the first set consisting of one or more positive plates made up into a single group, and the second of one or more negative plates made up into a separate group.

Taking first a battery in a normal charged condition, the positive plates contain active chemical material called lead peroxide (PbO_2), and the active material on the negative plates will be pure lead (Pb).

Immediately a current is taken from the cell the acid in which the plates are immersed—which is chemically classified as H_2SO_4—is split up by the action of the current into hydrogen (H_2) and sulphion (SO_4). The hydrogen passes in the direction of the current, and is liberated at the positive plates, combines with some of the oxygen in the lead peroxide on these plates, forming water (H_2O) and converting the lead peroxide into lead oxide (PbO).

This lead oxide is theoretically assumed to combine immediately with a part of the electrolite (H_2SO_4), the result being the formation of lead sulphate ($PbSO_4$) on the positive plates and the additional formation of water (H_2O).

The lead sulphate, which is also dispersed by the action of the current, combines with the spongy lead (Pb) on the negative plates, forming lead sulphate on these plates as well as on the positive plates.

It will be seen, therefore, that the effect of the discharged current from the cell is to convert the original lead peroxide on the positive plates and the pure lead on the negative plates to the same chemical substance, namely, lead sulphate. Since water is liberated the specific gravity of the acid will obviously be weakened during discharge.

The cell will continue to give a current until all the active material on both sides of plates is entirely converted to lead sulphate. In practice, however, the discharging of the cell is not taken to its extreme limit and a state of normal discharge is held to be reached only when a proportion of the material has been changed. During normal discharge the cell voltage will be from 2 to 2·1 volts. When the discharge continues beyond a certain point, the voltage will begin to drop rather suddenly, and immediately the voltage has reduced to a figure of 1·75 to 1·8, the cell is held to be discharged and to require recharging.

The chemical action which takes place when the cell is recharged is the reverse of the action during discharging. All the lead sulphate ($PbSO_4$) on the positive plates is converted back into peroxide of lead (PbO_2), and the lead sulphate on the negative plates is converted back into spongy lead. The density or specific gravity of the acid increases because the SO_4 part of the lead sulphate combines with the hydrogen in the acid, forming H_2SO_4, or sulphuric acid.

The chemical formula as expressed above indicates that the change which occurs during charging and discharging is entirely chemical. The practical evidence of this lies in the variations which occur in the density of the acid, in the voltage of the cell, in its temperature, in the colour of the plates and in the gassing which takes place when the cell is fully charged. All these various indications are important.

When the cell is discharged the normal discharge current should not appreciably be exceeded, neither should the discharge be continued after the cell has reached its normal discharge voltage of 1·8 volts, as otherwise the cells will be harmed.

In recharging the battery care must be taken not to exceed a safe value of charging at any time, or to continue the charging for too long a period, and a check must be made of the value of the voltage and specific gravity which will serve as an indication when the cell has been completely charged.

One of the most important changes which occurs is the variation of voltage, since this determines the whole principle of battery charging.

It has previously been stated that the voltage of a cell when normally discharged is 1·8 volts. As the cell becomes charged and as the active material becomes converted from its discharged condition into its charged condition, the voltage of the cell will continuously rise until it reaches a value of approximately 2·5 to 2·7 volts.

In view of the fact that the process of charging a battery consists of passing a current through it, the voltage applied to the battery must obviously be in excess of the voltage of the battery itself at any state of charge in order that a flow of current through the battery can be obtained. The voltage applied to the cell must be sufficiently in excess of the voltage of the cell itself, i.e. the back E.M.F., so that the difference divided by the resistance of the cell equals the charging current required.

In other words, the charging rate $= \dfrac{\mathrm{E}a - \mathrm{E}f}{\mathrm{R}}$

where $\mathrm{E}a$ = applied voltage,
$\mathrm{E}f$ = back E.M.F., and
R = resistance of the cell.

Thus, assuming a single cell with discharge voltage of 1·8 and applied voltage of 2 volts and a cell resistance of 0·1 ohm, the charging current will be

$$\frac{2 - 1{\cdot}8}{0{\cdot}1} = 2 \text{ amperes.}$$

It will be obvious that as the back E.M.F. of the cell increases, the applied voltage must also increase in order to maintain the charging current. Thus, when the back E.M.F. of the cell reaches 2 volts, the applied voltage must be increased to 2·2 volts. This increase of charging voltage must continue until the cell is completely charged, by which time its voltage will be approximately 2·5 volts. In other words, for normal recharging we require a voltage of 2·5 volts for every cell we desire to charge in series.

The process of commercial recharging consists in the provision of efficient methods of charging all types and sizes of

cells, both car and radio. It is essential to use direct current for battery charging and it is further essential—as will have been indicated by the foregoing—to provide a suitable value of D.C. voltage which will be in proportion to the number of cells to be charged.

In the case of direct current supplies, the commercial battery charger will, therefore, consist of means of reducing the mains D.C. voltage to a suitable value, and in the case of A.C. supplies it will be necessary to provide equipment which will firstly convert A.C. into D.C. and then provide the necessary value of D.C. voltage. The exact means by which this reduction and/or transformation is carried out distinguishes the various types of commercial battery charging equipment used in service.

How to Reduce the Voltage with D.C. Supply.—In the case of direct-current supplies, we can reduce the voltage to a suitable value by means of lamps or resistances, or alternatively a motor driven from the D.C. mains drives the dynamo which generates a given value of D.C. output in amperes and volts.

With A.C. Supply.—In the case of alternating current supplies, we can use a motor generator or, alternatively, means of rectifying the current from A.C. to D.C., either by a rotary rectifier or by a static rectifier such as the oxide cathode, metal rectifier or mercury arc rectifier. In all instances, however, the final result is the same, i.e. the provision of a given D.C. voltage and current.

The exact type of battery charger used is of considerable commercial importance, since the design of the battery charger determines the cost and quality of re-charging and the standard of the charging service which is given.

Constant Current System.—Since the maximum normal voltage of a fully charged cell is approximately 2·5 volts, this value of voltage is necessary for each cell which it is required to charge in series. Thus, to charge 12 cells, the value of the applied voltage would be $12 \times 2{\cdot}5 = 30$ volts. To charge 30 cells the applied voltage would be $30 \times 2{\cdot}5 = 75$ volts.

In the same way the number of cells which can be charged from a given D.C. voltage can be obtained by dividing the

D.C. CHARGING CIRCUITS

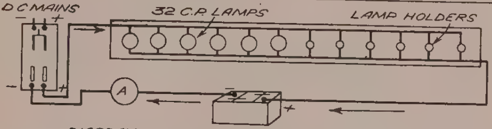


DIAGRAM OF A TYPICAL LAMP RESISTANCE BOARD

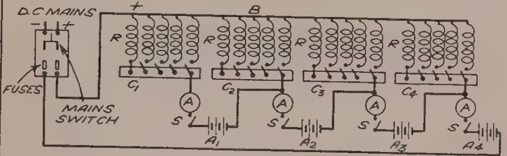
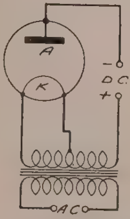
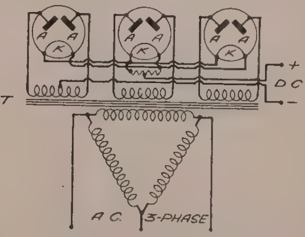


DIAGRAM OF CASCADE RESISTANCES FOR CHARGING BATTERIES ON D.C SUPPLY

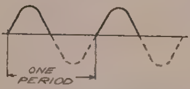
RECTIFIER CHARGING CIRCUITS



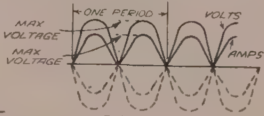
SCHEMATIC DIAGRAM OF A SIMPLE RECTIFIER



DIAG OF CONNECTIONS FOR A 3-PHASE 3-ANODE VALVE RECTIFIER



SHOWING EXTENT OF CONVERSION OF A C TO A UNIDIRECTIONAL FLOW OF CURRENT



SHOWING THE RESULTANT WAVE-FORM OBTAINED BY FULL-WAVE RECTIFICATION

voltage by 2·5. A 100-volt D.C. circuit is capable of charging up to $\frac{100}{2\cdot5} = 40$ cells.

In charging by this method, the cells are connected in series. The same value of current will flow through the complete series group. If cells which are variable in capacity have to be charged it will be necessary to connect them into a number of groups so that alternative values of charging current can be obtained.

The Construction of a Modern Charger.—For satisfactory service a modern battery charger should therefore, preferably, consist of a number of charging circuits designed to give a variation of charging rates.

Adjustment of Charging Rate.—In order to obtain the correct value of charging current and to maintain this current at a constant rate it will be necessary to provide means on each charging circuit whereby the voltage applied to the cells on charge can be regulated firstly to the number of cells connected to the circuit, and secondly in accordance with their condition.

The best way of describing this feature is to take an example of, say, 12 2-volt cells to be charged at 3 amperes. The normal discharge voltage of 12 cells connected in series will be $12 \times 1\cdot8 = 21\cdot6$ volts.

Assuming the resistance of each cell as 0·1 ohm, the total resistance of the series group will be $12 \times 0\cdot1 = 1\cdot2$ ohms. Thus, to attain an initial charging current of 3 amperes the difference in voltage between the applied voltage and the back E.M.F. will be $3 \times 1\cdot2$ (ohms $\times$ amperes in accordance with Ohm's law) $= 3\cdot6$ volts.

The applied voltage would, therefore, need to be $21\cdot6 + 3\cdot6 = 25\cdot2$ volts. Thus, according to the formula previously expressed, the charging current will be

$$\frac{Ea - Ef}{R} = \frac{25\cdot2 - 21\cdot6}{1\cdot2} = \frac{3\cdot6}{1\cdot2} = 3 \text{ amperes.}$$

Immediately the cells begin to be charged the voltage will rise, and since this will reduce the difference between the applied voltage and the back E.M.F., the charging current will drop in proportion. In order to compensate for this the applied voltage must be increased. Thus, when the cell voltage is 2 volts per cell, i.e. total voltage $12 \times 2 = 24$ volts,

PARALLEL CHARGING CIRCUITS

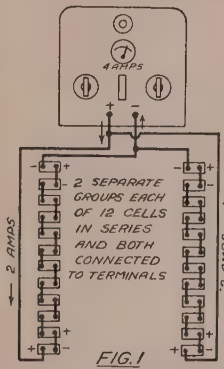


FIG. 1
BATTERY CHARGER WITH AN OUTPUT OF 4 AMPS FITTED WITH ONLY ONE CHARGING CIRCUIT.

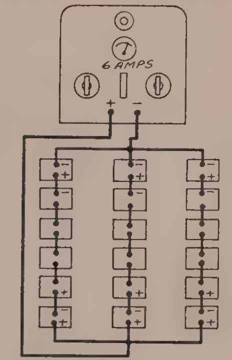


FIG. 2 THREE GROUPS EACH OF SIX CELLS CONNECTED TO A 6-AMPERE SINGLE-CIRCUIT CHARGER.

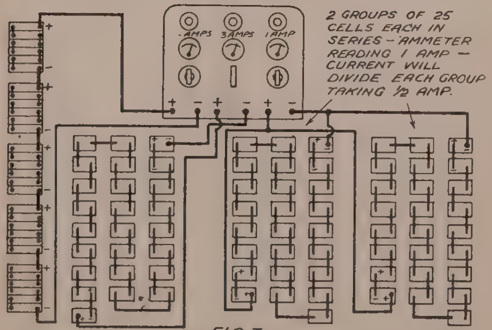


FIG 3
A TYPICAL EXAMPLE OF SERIES & PARALLEL CHARGING.

the applied voltage must be increased to a value 3·6 volts in excess of this voltage, namely, 27·6 volts.

At all times until the cells are completely charged the applied voltage must be sufficiently in excess of the variable back E.M.F. in order to provide the required constant charging current.

Charging Resistances.—The way in which this variation of applied voltage is obtained is by the use of charging resistances. In the above example the normal voltage of the charger is 30 volts. In order to begin charging we require an applied voltage of only 25·2 volts. We therefore provide a charging resistance of sufficient value to reduce the 30 volts to 25·2 volts, and by making the resistance variable we can reduce the amount of resistance and thereby reduce the voltage drop until, when all cells are charged, the resistance is entirely cut out.

Handling Various Sizes of Cells.—The difficulty which sometimes exists is that there may be a rather awkward variation in the number of cells to be charged. Let us assume that we require to charge the following :—

1. 3 12-volt car batteries (18 cells) at 5 amperes.
2. 20 radio cells at 3 amperes.
3. 28 radio cells at 1 ampere.

The maximum number of cells is 28, and therefore the maximum voltage of the charging plant will need to be $28 \times 2{\cdot}5 = 70$. In practice it will be preferable to use a 75-volt plant which is standard. A suitable plant would, therefore, be a charger with three circuits, giving charging rates of 6 amperes, 3 amperes and 1 ampere respectively. The maximum voltage of the charger is 75 volts.

It is essential to use direct current for battery charging. Where the incoming supply is alternating current, means must, therefore, be provided to convert this current from A.C. to D.C.

There are several commercial methods of obtaining this conversion, the equipment available comprising motor generators, commutating rectifiers, metal rectifiers and valve rectifiers.

With motor generators, pure direct current is generated by means of a dynamo which is driven by an A.C. motor. In effect, we provide an independent method of generation, designing the dynamo to have the requisite value of voltage

and current output determined by the size and number of the batteries to be charged.

In the case of commutating rectifiers and metal and valve rectifiers, a different principle is adopted. The actual incoming A.C. supply is converted from a current which continuously reverses into a current which flows in one direction only and thereby becomes suitable for battery charging.

The Theory of Rectification.—The basic theory of rectification is the provision of means which will permit an applied alternating current to flow through the rectifying unit in one direction only.

Various units have been designed which have this property of permitting a current to flow in one direction only, such units comprising a commutating rectifier which operates on the rotary principle, and oxide cathode or mercury arc valves and metal rectifiers where the operation is static, no moving parts being used.

Since the principle is the same in all cases it will be convenient for simplicity to consider the operation of a modern oxide cathode rectifier. The essential part of such a rectifier is the rectifying tube which converts A.C. to D.C. because of its property of permitting current to pass in one direction only. A typical example of an oxide cathode valve is illustrated.

Since it is usually necessary to obtain a given value of direct current, a transformer is usually associated with the rectifying valve in order to change the value of the A.C. supply before it is fed to the valve, and in some cases to alter the number of phases available for rectification.

The rectifying valve is fitted with two electrodes between which, when the valve is in operation, a flow of electrons is established, this flow being equivalent to a flow of electric current. One electrode is hot and the other cold, and under this condition if a positive potential is applied to the cold electrode, called the *anode*, and a negative potential applied to the hot electrode, called the *cathode*, a flow of electrons will be established. Immediately, however, the polarity is reversed, this flow will cease, thus providing the required property of a unit which will permit current to flow in one direction only.

The lower diagram on page 97 indicates the extent of this conversion, the negative flow being "cut off" only, the positive impulses of current being permitted to flow.

The foregoing principle effectively explains the basic prin-

ciple of rectification. The only difference between the various types of rectifiers is the unit employed to effect the unidirectional flow of current.

The Metal Rectifier.—A type of rectifier closely similar to the oxide cathode type is the metal rectifier. Effectively the only difference between the oxide cathode and the metal rectifier is that with the latter the oxide cathode valve is replaced by a metal rectifying unit consisting of a combination of copper and copper oxide placed intimately in contact.

It is found that under this condition the electrical resistance through the metal and oxide combination is relatively low in the oxide-to-metal direction and very high in the metal-to-oxide direction. The resistance in the metal-to-oxide direction is 1,000 or more times the resistance in the opposite direction, thus providing a unit which—from a practical point of view—will permit current to pass in one direction only.

Constant-potential System.—In constant potential charging, a constant voltage is applied, and the charging current will vary according to the state of charge of the battery.

Motor generators or commutating rectifiers are used, and are usually designed to give a constant $7\frac{1}{2}$ or 15 volts and a comparatively large current output to copper busbars.

The batteries to be charged are connected in 6- or 12-volt units across the positive and negative busbars. Some sets have three busbars, giving two voltages, $7\frac{1}{2}$ across the centre and either of the two outer busbars, and 15 across the two outers.

The current flowing through each cell is equal to:

$$\frac{\text{Voltage of circuit} - \text{voltage of cell.}}{\text{Resistance of cell}}$$

Thus, when the battery is first connected, a high charging current flows into it, but as the terminal voltage of the battery rises (as the battery becomes charged), the charging current tapers off automatically. At the end of the charge, the voltage of the battery will be equal to the voltage of the busbars, and, consequently, no current will flow.

With the constant potential method, the time taken to charge healthy cells is considerably less than with the constant current method.

If a battery is badly run down, or unhealthy, it is desirable to provide connecting leads incorporating a sufficient amount of resistance to reduce the initial current to a suitable value, which in practice is 10 or 20 amps., depending upon the actual battery.

TRANSMISSION AND DISTRIBUTION

Two-Wire D.C.—Referring to Fig. 1, the volt drop in each conductor = IR, therefore the total volt drop = 2IR. The voltage drop will therefore be given by E − V = 2IR. The power loss in each conductor = I^2R. Therefore total power loss = $2I^2R$.

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{VI}{EI} = \frac{EI - 2I^2R}{EI}$$

$$= \frac{VI}{VI + 2I^2R}$$

$$\text{Voltage regulation} = \frac{E - V}{V} = \frac{2IR}{V}.$$

A.C. Single Phase.—Referring to diagram in Fig. 2, the constants are shown as L and R, where L is the inductance power conductor and R is the resistance power conductor (capacitance is neglected here).

Taking the power factor of the load as $\cos\phi$, the relation between the delivery volts, V, and the supply volts, E, will be given by $E = \sqrt{(V\cos\phi + 2IR)^2 + (V\sin\phi + 2IX)^2}$. The volt drop and regulation can be found from the difference between E and V.

An approximate value for the volt drop per conductor is given by $IR\cos\phi + IX\sin\phi$. So that the total volt drop will be $2(IR\cos\phi + IX\sin\phi)$.

The power loss per line is I^2R giving a total power loss of $2I^2R$. The power factor at the supply end is found from

$$\tan\phi_1 = \frac{(V\sin\phi + 2IX)}{(V\cos\phi + 2IR)}$$

and the efficiency will be found by

$$\frac{VI\cos\phi}{VI\cos\phi + 2I^2R}.$$

Three-Phase A.C.—Neglecting capacitance, the line constants will be as shown in Fig. 3 and the following details refer to a balanced load.

Reactance and resistance drops per conductor will be IX and IR. But for three-phase reactance and resistance drops per phase will be $\sqrt{3}IX$ and $\sqrt{3}IR$. The relation between V and E will then be given by

$$E = \sqrt{(V\cos\phi + \sqrt{3}IR)^2 + (V\sin\phi + \sqrt{3}XI)^2}.$$

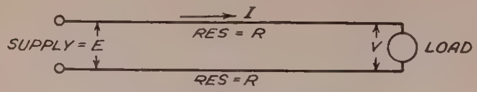


FIG. 1 — D.C. 2-WIRE

FIG. 2 — A.C. SINGLE-PHASE

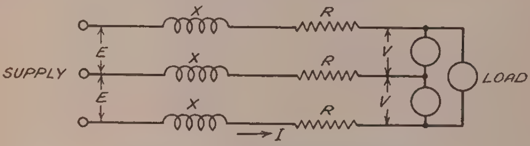


FIG. 3 — A.C. THREE-PHASE

VECTOR DIAGRAM FOR 3-PHASE LINE

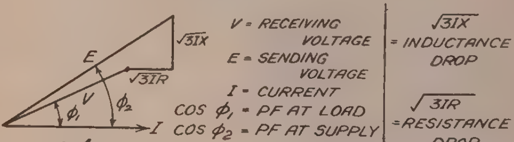
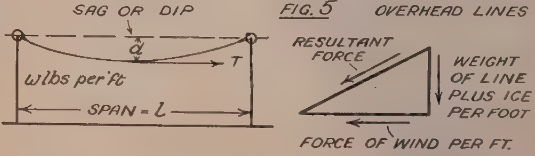


FIG. 4

FIG. 5 OVERHEAD LINES



The power factor at the supply end can then be obtained from

$$\tan \phi_1 = \frac{(V \sin \phi + \sqrt{3}IX)}{(V \cos \phi + \sqrt{3}IR)}.$$

The loss in each line will be I^2R, the total loss in this case being $3I^2R$. The efficiency can be found from

$$\frac{\sqrt{3}VI \cos \phi}{\sqrt{3}VI \cos \phi + 3I^2R}.$$

The voltage regulation of the line will be found from $\frac{E - V}{V}$.

The Vector Diagram for a three-phase circuit is shown in Fig. 4, and this can be used for single phase by omitting the root $\sqrt{3}$ before the IR and IX.

Kelvin's Law.—In any transmission line it can be shown that the maximum economy is obtained when the annual capital cost of the line equals the cost of the energy loss in transmission during the year. This is known as Kelvin's Law and is used as a guide for determining the size which should be used for a transmission line. The result obtained by applying Kelvin's law must be considered also from the point of view of volt drop, current-carrying capacity and mechanical construction.

The capital cost of a line is the cost (usually taken over a year) for the interest on the capital expended, plus depreciation and maintenance. Usually a figure of between 10 per cent. and 20 per cent. of the capital cost is taken to cover these items. The energy loss in the line during the year can only be estimated and the following equation can be used

$$\frac{eBs}{100} = \frac{mI^2Rp \times 8760}{1000 \times 240}$$

where e = interest and depreciation in percentage per annum
B = cost per thousand yards of line per square inch of cross-section in £
m = number of conductors
I = R.M.S. value of the current taken over a year
R = the resistance of one conductor per thousand yards
p = the cost in pence for energy per unit.

From the above equation the ideal section for any transmission line can be obtained and the nearest standard size larger should first be considered. Full consideration must be given to the other points mentioned above.

Mechanical Strength of Overhead Lines.—Referring to Fig. 5, the stress in an overhead conductor will be found from the formula

$$\text{Tension in conductor} = T = \frac{wl^2}{8d}$$

where w = weight per foot
l = span in feet
d = sag in feet.

The conductor must then be designed to withstand this stress or tension, allowing for the necessary factor of safety (this varies from 2·5 to 6·0). The section will therefore be given by

$$T = s \times f_t \times \frac{1}{\text{factor of safety}}$$

where s = area of cross-section
f_t = breaking stress of conductor per square inch of cross-section.

In many cases the section is fixed and it is then necessary to fix the value of d (sag or dip) to give a safe value for T. In this case T is fixed by

$$T = s \times f_t \times \frac{1}{\text{factor of safety}}$$

and as $T = \dfrac{wl^2}{8d}$ then $d = \dfrac{wl^2}{8T}$.

Allowance for Ice.—The weight of the conductor will be increased by an ice deposit and the increase in weight is given by the expression

$w_i = 1{\cdot}244i(d + i)$ lb. per ft.

where w_i = increase in weight due to ice
d = diameter of conductor in inches
i = radial thickness of ice in inches.

This weight must be added to the weight of the conductor which is used in the formula given above.

Allowance for Wind.—The resultant force on the conductor will be found by adding "vectorially" the weight of the conductor plus the weight of ice to the pressure exerted by the wind. Referring to Fig. 5, the total weight of the line, taking into account ice and wind, will be given by

$$\text{Resultant } w = \sqrt{(w_c + w_i)^2 + (w_w)^2}$$

where w_c = weight of conductor per foot
w_i = weight of ice per foot
w_w = force of wind per foot.

CONSTANTS FOR OVERHEAD LINES

Inductance.—The inductance of round parallel conductors carrying currents of equal magnitude can be shown to be

$$L = 2 \log_e \frac{d}{r} + \frac{\mu}{2} \text{ c.g.s. units per cm. per conductor,}$$

where d is the distance between centres (in centimetres), r is the radius of each conductor and μ is the permeability of the conductor. As the value of μ can be taken as unity we get

$$L = 2 \log_e \frac{d}{r} + \frac{1}{2} \text{ c.g.s. units per cm. per conductor.}$$

For practical use it is usual to convert this to value per mile or per 1,000 yards and the above formula becomes:

$$L = 0{\cdot}080 + 0{\cdot}741 \log_{10} \frac{d}{r} \text{ millihenries per mile}$$

$$\text{or } L = 0{\cdot}0454 + 0{\cdot}421 \log_{10} \frac{d}{r} \text{ millihenries per 1,000 yds.}$$

For three-phase lines the inductance per conductor will be the same value for equally spaced conductors. For unequal spacing an average value is obtainable, viz.:

$$L = 0{\cdot}080 + 0{\cdot}741 \log_{10} \frac{\sqrt[3]{d_1 d_2 d_3}}{r} \text{ millihenries per mile,}$$

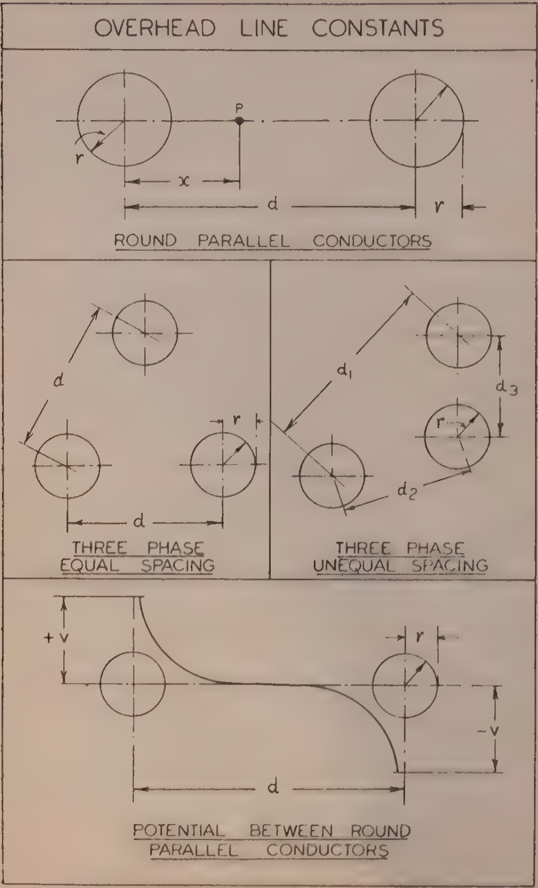
where d_1, d_2 and d_3 are the respective centres.

Capacitance.—Using the same data as for inductance above, it can be shown that the capacitance *of each conductor* is given by

$$C = \frac{1}{2 \log_e \frac{d}{r}} \text{ c.g.s. electrostatic units per cm. length.}$$

Here again it is more convenient to use miles or 1,000 yards with practical units and thus

$$C = \frac{0{\cdot}0388}{\log_{10} \frac{d}{r}} \text{ microfarads per mile}$$


OVERHEAD LINE CONSTANTS
P
r
x
d
r
ROUND PARALLEL CONDUCTORS
d
r
d
THREE PHASE
EQUAL SPACING
d1
d3
r
d2
THREE PHASE
UNEQUAL SPACING
+V
r
−V
d
POTENTIAL BETWEEN ROUND
PARALLEL CONDUCTORS

or $$C = \frac{0 \cdot 022}{\log_{10}\frac{d}{r}} \text{ microfarads per 1,000 yds.}$$

The effect of the earth on a single conductor obtained in a similar way will be

$$C = \frac{0 \cdot 0388}{\log_{10}\frac{2h}{r}} \text{ microfarads per mile,}$$

where h is the distance of the centre of the conductor to the earth.

It can be shown that the effect of the earth does not cause any important alteration in the capacitance of an overhead line and for the type of lines used to-day it can be neglected.

For three-phase overhead lines the values per conductor are the same for equally spaced conductors. For unequal spacing an average value is obtainable, viz.:

$$C = \frac{0 \cdot 0388}{\log_{10}\frac{\sqrt[3]{d_1 d_2 d_3}}{r}} \text{ microfarads per mile,}$$

where d_1, d_2 and d_3 are the respective centres.

Potential Gradient.—The variation of potential between two parallel conductors will be as shown in the bottom diagram. It will be seen that the curve is steepest at the surface of the conductor and it is at this point that the maximum potential gradient occurs for normal overhead lines where the value of r will be small compared with d.

The value of the potential gradient at this point where it is a maximum is given by

$$g_{\text{max.}} = \frac{E}{r \log_e \frac{d}{r}} \text{ volts per cm.,}$$

where $g_{\text{max.}}$ = potential gradient

E = volts *to neutral*

Note.—For single-phase $E = \frac{V}{2}$

For three-phase $E = \frac{V}{\sqrt{3}}$

ALUMINIUM OVERHEAD LINES

The use of steel-cored aluminium for the British "Grid," involving more than 20,000 miles of conductor, brought aluminium to the fore, and it is now used on all types of overhead lines from low-voltage distribution lines to the most important high-tension lines all over the world.

One of the reasons for its adoption is that for normal market prices steel-cored aluminium conductors are cheaper as regards first cost. In addition there is the fact that for the same conductivity they are 50 per cent. stronger and approximately 20 per cent. lighter, with the result that the sag for a given span will be less. In practice this advantage is used to increase the span length, thus reducing the number of supports.

It will therefore be readily understood that the use of aluminium results in definite savings as regards first cost and upkeep, together with increased reliability due to a lesser number of points at which trouble may arise.

The fundamental principle on which overhead lines are designed is that all the current is carried by the aluminium, whereas the strength of the conductor is taken as 85 per cent. of the strength of the steel core, plus 98 per cent. of that of the aluminium, these values being based on the strengths of the component wires before stranding.

Corona.—The increased external diameter is an advantage in that corona losses will be less than if smaller diameter conductors were used.

The following tables give useful data with reference to aluminium generally and also various properties and constants of aluminium conductors. These tables have been compiled with the assistance of the British Aluminium Company, Ltd.

PHYSICAL PROPERTIES OF ALUMINIUM

Property.	Value.	Authority.
PHYSICAL CONSTANTS		
Atomic Weight (Oxygen = 16)	26·97	Int. Atomic Wt. Comm., 1929.
Spec. Ht., 20°–400° C. (av.) cals.	0·24	Int. Crit. Tables Formula.
Spec. Thermal Conductivity in cals. per cm. cube per degree C. per sec., at 0° C.	0·502	Bailey, Proc. Roy. Soc. A., 134, 57–76, 1931.
Approx. Relative Heat Conductivity (Silver = 100%)	51·8	
Melting Point (99·97% pure) ° Cent.	659·8	Edwards, J., American Electrochem. Soc., 1925.
Melting Point (99·66% pure) ° Cent.	658·7	
Boiling Point, ° Cent.	1800	Greenwood, Proc. Royal Soc., 82, 1909.
Latent Ht. of Fusion, cals. per gm.	92·4	Awbery & Griffiths, Proc. Phys. Soc., Lond., Vol. 38, pt. 5, Aug. 15, 1926.
Total Ht. referred to 20° C.: calories per gm. 400° C.	88	
„ „ 600° C.	146	
„ „ 700° C.	267	
Vapour Pressure at 658·7° C., mm. of Mercury	$1{\cdot}0 \times 10^{-43}$	Richards, Jour. Franklin Inst., Vol. 187, 1919.
Heat of Combustion to Al_2O_3 per gm. mol., cals.	383,900	A.S.S.T. Handbook.
Coeff. of Linear Expansion/° C.		
H. D. Wire 0°–30° C.	23×10^{-6}	Int. Electrotech. Comm.
Rolled metal (normal purity) Average value, 20°–100° C.	24×10^{-6}	Based on Hidnert. U.S. Bureau of Standards Paper No. 497.
„ „ 20°–300° C.	$26{\cdot}7 \times 10^{-6}$	
„ „ 20°–600° C.	$28{\cdot}6 \times 10^{-6}$	
Specific Gravity :—		
H.D. Wire (elec. conductors)	2·703	B.S.S. No. 215, 1934.
Rolled Sheet (normal purity)	2·71	British Aluminium Co., Ltd.
Molten (99·75% pure), 658·7° C.	2·382	Edwards & Moorman, Chem. Met. Eng., Vol. 24, pp. 61–4, 1921.
„ „ 1100° C.	2·262	
Wt. of 1 cubic ft. of Aluminium (normal purity) lb.	169·18	Calculated from Specific Gravity.
Wt. of 1 cubic ft. of Aluminium (high purity) lb.	168·74	
MECHANICAL CONSTANTS		
Modulus of Elasticity, lb./sq. in.	$9{\cdot}9 \times 10^{6}$	B.S.S. No. 215, 1934.
Torsion Modulus, lb./sq. in.	$3{\cdot}87 \times 10^{6}$	Koch & Dannecker, Ann. d. Phys., 1915.
Poisson's Ratio	0·36	Bureau of Stands. Circ. No. 76, 1919.

PHYSICAL PROPERTIES OF ALUMINIUM

Property.	Value.	Authority.
Mechanical Constants (cont.)		
Tensile Strength of Sheet :		
Annealed, tons/sq. in. . .	5–6½	B.S.S. No. 2L17, 1922
Half Hard, tons/sq. in. . .	7–8½	B.S.S. No. 2L16, 1922.
Hard, tons/sq. in. . . .	9 (min.)	B.S.S. No. 2L4, 1922.
Percentage Elongation in 2 in. :		
Pure Castings, Sand . . .	20–30	British Aluminium Co., Ltd.
,, ,, Chill . . .	30–40	,, ,, ,,
Pure Sheet, Annealed . .	12–40	,, ,, ,,
,, ,, Half Hard . .	5–12	,, ,, ,,
,, ,, Hard . . .	2–8	,, ,, ,,
H.D. Wire	4–7	,, ,, ,,
Elastic Limit as Percentage of Tensile Strength of H.D. Wire	60	,, ,, ,,
Scleroscope Hardness (mag. ham.) :		
Annealed or Cast. . . .	5 to 5½	,, ,, ,,
Cold Rolled (0·128″–0·020″)	15 to 22	,, ,, ,,
Brinell Hardness, 1 mm./5 kgm. :		
Cast	20 to 28	,, ,, ,,
Annealed Sheet	19 to 23	,, ,, ,,
Hard Sheet	38 to 45	,, ,, ,,
ELECTRICAL CONSTANTS		
Max. Specific Res. for H.D. Wire at 20° C — microhms/cm. cube	2·8735	,, ,, ,,
microhms/in. cube	1·1313	,, ,, ,,
Standard Specific Res. for H.D. Wire at 20° C. — microhms/cm. cube	2·845	B.S.S. No. 215, 1934.
microhms/in. cube	1·1199	,, ,,
Coefficient of increase of res. with temp. for H.D. wire at 60° F. (15·6° C.) — ° C.	0·00407	,, ,,
° F.	0·00226	,, ,,
Electrochem. equivalent, grs. per coulomb	0·00009316	Calculated from stand. val. for silver.
Electrolytic solution potential against a normal hydrogen electrode (in normal aluminium sulphate) volts .	1·3	Bureau of Stands. Circ. 346.
Thermo-electromotive force against pure platinum for 99·97% Al. at 1 0° C., millivolts	+0·416	,, ,, ,,
Magnetic Susceptibility at 18° C.	0·63×10−	I.C.T., Vol. VI, p. 354.

WIRE AND CABLE CONSTANTS FOR ALUMINIUM CONDUCTORS

Weight of Cable

To calculate the weight per 1,000 yards, mile or kilometre of any size of bare cable or wire, multiply the gross sectional area by the appropriate constant given in the table below.

In the case of a steel-cored aluminium cable, calculate the weights of the steel core and aluminium portion separately and add together to give the weight of the composite cable.

Type of Conductor.	Total No. of Wires in Conductor.	WEIGHT.			RESISTANCE at 20° C. (68° F.).		
		lb./ 1,000 yds. per sq. in.	lb./ mile per sq. in.	kg./ km. per sq. mm.	ohm/ 1,000 yds. per sq. in.	ohm/ mile per sq. in.	ohm/ km. per sq. mm.
Aluminium wire	1	3,515	6,187	2·703	0·04031	0·07094	28·45
Plain aluminium conductor	3	3,561	6,267	2·738	0·04084	0·07187	28·82
	7	3,560	6,265	2·738	0·04082	0·07184	28·80
	19	3,574	6,290	2·748	0·04098	0·07212	28·92
	37	3,595	6,326	2·764	0·04122	0·07254	29·09
Aluminium portion of steel-cored aluminium conductor	7, 13 and 14	3,561	6,267	2·738	0·04084	0·07187	28·82
	33, 37 and 61	3,602	6,339	2·770	0·04132	0·07272	29·16
Steel wire	1	10,196	17,945	7·840	Conductivity neglected		
Steel cable	7	10,263	18,060	7·892			

The constants given in the table are based on specific gravities for hard-drawn aluminium wire and galvanized steel wire of 2·703 and 7·84 (average) respectively.

Resistance of Cable

To calculate the resistance per 1,000 yards, mile or kilometre of any size of bare cable or wire, divide the appropriate constant given in the table by the gross aluminium sectional area. For steel-cored aluminium conductor, the resistance of the steel core is neglected. The constants give the resistances at 20° C. (68° F.) and are based upon a standard specific resistance for aluminium of 1·1199 microhms per inch cube (2·845 microhms per cm. cube) at this temperature; i.e. a standard conductivity of 60·6 per cent. that of pure annealed copper.

Change of Resistance with Temperature

The change in resistance of conductors with temperature can be calculated from the formula:

$$R_T = R_t\,[1 + \alpha_t\,(T - t)]$$

where R_T = Resistance at T°, R_t = Resistance at t°, α_t = Coefficient at t°.

The coefficient of increase of resistance with temperature varies according to the datum temperature taken. At 60° F. (15·6° C.) the value of the coefficient is taken as 0·00407 per ° C. and at 20° C. it is 0·00400 per ° C.

Overall Diameter of Cable

Multiply the wire diameter D by the appropriate constant in the table below:

No. of wires of equal diam.	3	4	7	12	19	37	61	91
Diameter Constant.	2·155	2·41	3	4·155	5	7	9	11

Where all the wires are not of the same diameter, as in the case of certain standard constructions of steel-cored aluminium, the overall diameter of the cable is found by calculating the diameter of the core from the above table and adding twice the product of the aluminium wire diameter multiplied by the number of layers of aluminium wires.

BRITISH REGULATIONS FOR OVERHEAD LINES

The following are the main requirements of the Electricity Commissioners of Great Britain for safe erection and operation of overhead lines as set out in El.C. 53 (Revised 1931):

1. Factor of Safety in Conductors.

Working Pressure in Volts.	Simultaneous Loading Conditions.			Factor of Safety in Conductors.
	Wind Pressure.	Temperature.	Ice Loading.	
Exceeding 650 D.C. or 325 A.C.	8 lb./sq. ft. on projected area of ice-covered conductor	22° F.	⅜″ radial thickness (Assume wt. of ice as 57 lb./cu. ft.)	2

For voltages not exceeding 650 D.C. or 325 A.C. the same regulations apply, but with the exception that the ice load is taken as $\frac{3}{16}$ inch radial thickness.

2. Factor of Safety in Supports.

Factor of Safety in Supports.		Foundations.
Transverse Direction.	Longitudinal Direction.	
2·5 for iron or steel 3·5 for wood or ferro-concrete	Strength to be not less than one-quarter the transverse strength	Must hold support against specified loads without movement

The above factors of safety are calculated on the assumption that all conductors, earth wires, etc., are at a temperature of 22° F. and are covered with ice of specified radial thickness, and that, together with the supports, they are subjected to a wind pressure of 8 lb./sq. ft., calculated on the whole of the projected area, exerted at right angles to the line.

The wind pressure on the lee side of A or H poles and lattice steel structures shall be taken as one half the wind pressure on the windward side members. For lattice steel structures, the above factor of safety is calculated on the crippling load of struts or the elastic limit of ties.

3. Minimum Ground Clearances at 122° F.

Working Pressure in Volts.	Minimum Ground Clearance.
Not exceeding 66,000 . .	20 feet
66,000 to 110,000 . . .	21 feet
110,000 to 165,000 . .	22 feet
Exceeding 165,000 . . .	23 feet

For voltages not exceeding 650 volts D.C. or 325 volts A.C. the minimum ground clearances of any line conductor (other than a service line), earth wire or auxiliary conductor at any point of the span are as follows:

19 feet across a public road.
17 feet in other positions.
15 feet in positions inaccessible to vehicular traffic.

For service lines:

19 feet across a carriage way.
17 feet along a carriage way.

UNDERGROUND CABLE CONSTANTS

Insulation Resistance.—The insulation resistance is not directly proportional to the radial thickness of insulation and can be found from

$$R = \frac{\rho}{2\pi} \log_e \frac{R}{r}$$

where ρ is the specific resistance of the insulating material. This is more conveniently expressed in ohms or megohms per mile or per 1,000 yards. This is given by

$$R = 2{\cdot}28\rho \log_{10} \frac{R}{r} \times 10^{-12} \text{ megohms per mile}$$

or

$$R = 1{\cdot}29\rho \log_{10} \frac{R}{r} \times 10^{-12} \text{ megohms per 1,000 yds.}$$

Capacitance.—The capacitance of a single-core cable is given by

$$C = \frac{\epsilon}{2 \log_e \frac{R}{r}} \text{ c.g.s. electrostatics per cm. of length,}$$

where ϵ is the specific inductive capacity or dielectric constant.

Expressed in more practical units, this becomes

$$C = \frac{0{\cdot}0388\epsilon}{\log_{10} \frac{R}{r}} \text{ microfarads per mile}$$

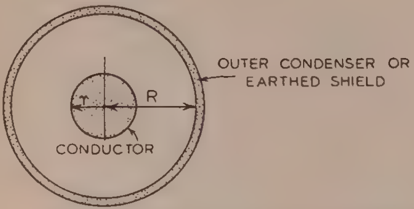
or

$$C = \frac{0{\cdot}022\epsilon}{\log_{10} \frac{R}{r}} \text{ microfarads per 1,000 yds.}$$

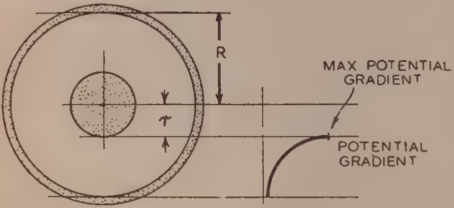
Voltage Gradient.—The question of voltage or potential gradient in insulated cables is an important one as continued increase in radial thickness does not appreciably add to the permissible working voltage.

The voltage gradient curve will be seen from the diagram, and as in the case of overhead conductors the maximum gradient occurs at the surface of the conductor or the core

UNDERGROUND CABLE CONSTANTS



SINGLE CORE OR CONCENTRIC CABLE



POTENTIAL GRADIENT IN SINGLE CORE CABLE

TEST (1) = ONE CONDUCTOR TO OTHER TWO EARTHED TO SHEATH
$= 2C + S$

TEST (2) = THREE CONDUCTORS BUNCHED TO EARTH
$= 3S$

FROM THESE C AND S CAN BE FOUND

CAPACITY TO NEUTRAL $= S + 3C = \frac{9 \times (1) - (2)}{6}$

CAPACITANCE IN 3-CORE CABLES

in this case. The value of this potential gradient at the surface of the core can be calculated from

$$g_{\text{max.}} = \frac{E}{r \log_e \frac{R}{r}} \text{ volts per cm.}$$

As it is necessary to keep this value as low as possible it is important to note that the minimum value is obtained when $\log_e \frac{R}{r} = 1$, i.e. when $R = 2{\cdot}718r$.

Thus the most efficient cable is obtained when the outer radius is 2·718 times the radius of the core—in which case the maximum voltage gradient will be

$$g_{\text{max.}} = \frac{E}{r} \text{ volts per cm.}$$

One method, therefore, of designing cables to withstand the maximum pressure is to increase the core diameter by making it hollow or filled with a suitable material. This practice is adopted for certain high-voltage cables to-day.

UNDERGROUND CABLES

All cables for ordinary transmission purposes usually have copper conductors, insulated with impregnated paper and covered overall with a lead sheath. For certain special purposes in mines and other situations, bitumen and other materials are used for insulation, but these are rather particular cases where it is impracticable to carry out the details connected with the sealing and installation of paper insulated cables.

The lead sheath is essential to prevent access of moisture to the paper, which is hygroscopic. It also forms a binder or protection, but armouring is added to give final mechanical protection where this is required.

The paper used is generally a wood-pulp paper specially manufactured for the purpose, and it must be comparatively strong and elastic as well as able to absorb the impregnating oil satisfactorily.

The lead sheathing usually contains a small percentage of antimony and cadmium in order to increase its strength and prevent cracking.

It is of course essential for moisture to be unable to gain access to the insulation, and all joints must be made in special boxes whereby the lead sheath is joined as one continuous sealed tube. Terminal boxes are used for the ends of the cable and are filled with suitable compound to form the required seal.

High-Voltage Cables.—As will be seen from the notes on underground cable constants the voltage gradient at the surface of the core of a cable is severe and limits the voltage for which cables can be used. One method of overcoming this is to increase the diameter of the core or cores, but the stress on the insulation must be kept within certain limits, and there is also a limit to the physical size of a cable on account of its cost.

The voltage limit can be raised by the use of *grading*, which is one of two types. One is called *capacitance* grading, in which the insulation consists of layers of different material, thus varying the permittivity inversely as the distance from the centre of the conductor. The working pressure of a cable of given size can be increased by 30 to 40 per cent. by this means.

The other type is termed intersheath or condenser grading, whereby insulated sheaths of lead are formed round the insulation at suitable distances from the core. By this means a series of condensers is formed and the total voltage spread between them. The distribution of the total voltage can be controlled by means of tappings from a transformer. This principle has been of more use in connection with condenser bushings for the lead-in to transformers and switchgear than for cables generally and other types of cables have been developed.

Capacitance grading has only been used to a very limited extent owing to manufacturing difficulties.

Types of Three-core Cables for High Voltage.—The simple three-core cable with an outside lead sheath—termed a *belted* cable—is not satisfactory on voltages such as 33 kV as it fails, due to electrostatic stresses at the surface of the cores. Owing to the formation of voids, local breakdown spreads and finally the cable fails.

One development has been the H-type cable (from the inventor Höchstädter), in which the three cores are formed into separate units over which a thin sheath of aluminium or copper is wound. These sheaths or screens are connected and earthed to the outer lead sheath. This construction keeps the stresses radial and also prevents core to core failure. A more solid insulation is formed and the cable is therefore less liable to internal distortion due to handling.

The principle of screening also appears in the S-L (Separate-Lead) cable in which the thin metal screens are replaced by three separate lead sheaths. In this cable the manufacturers are able to make a still more satisfactory cable as there are absolutely no irregular layers of insulation or filling—each single core unit being a complete cable.

Both of these cables can be used for 33 kV systems and are favoured in many cases for lower pressures.

For higher pressures single-core cables have usually been used until the introduction of oil-filled cables.

Oil-Filled H.T. Cables.—As one of the difficulties with solid paper insulated cables is the avoidance of voids and the drainage of oil from certain points, the use of oil under pressure has been used with considerable success. Most existing installations consist of single-core cables having a hollow or tube-like core through which the oil flows. The oil is kept under pressure by means of elevated storage tanks

at suitable points and which allow expansion and contraction.

Capacitance grading is obtained by using layers of paper of different porosity, and as the final impregnation is done after the lead sheathing has been formed, better drying out is effected.

Single-core cables working on 132,000 volts are now satisfactory and experimental sections are under test for higher pressures. High-voltage cables are of particular interest as regards terminal connections for overhead lines apart from their possible use for main transmission purposes. Three-core oil-filled cables are now in general use for 33 and 66 kV. In the case of three-core cables the oil is often carried by means of special ducts between the conductors.

Pressure Cables.—These are similar to H-type cables.

The cause of breakdown of high-pressure cables is often the ionization inside the voids, and as increased mechanical pressure raises the voltage required to set up ionization, this is one of the latest methods of making high-voltage cables.

A triangular outside lead sheath is used, protected by metal tape, and the cable is laid in a steel pipe which is filled with nitrogen under a pressure of 12 atmospheres or more.

Another form of super-tension cable is the gas-pressure type using hollow conductors. Several cable-makers are experimenting with gas-filled cables in various forms.

VOLTAGE REGULATION OR VARIATION

CONTROL and variation of voltage may be necessary for counteracting volt drop in a transmission line or for the purpose of giving a varying voltage for some process. Most voltage regulating equipment is for the former purpose, but many of the types of apparatus can be used for both purposes.

Tap-Changing Transformers.—This system is used by the C.E.B. on most of the grid lines covering the country. The principle is indicated in the diagram on page 124—this diagram shows a simple switching type which is only applicable where it is possible to interrupt the current while the tap-changing is taking place.

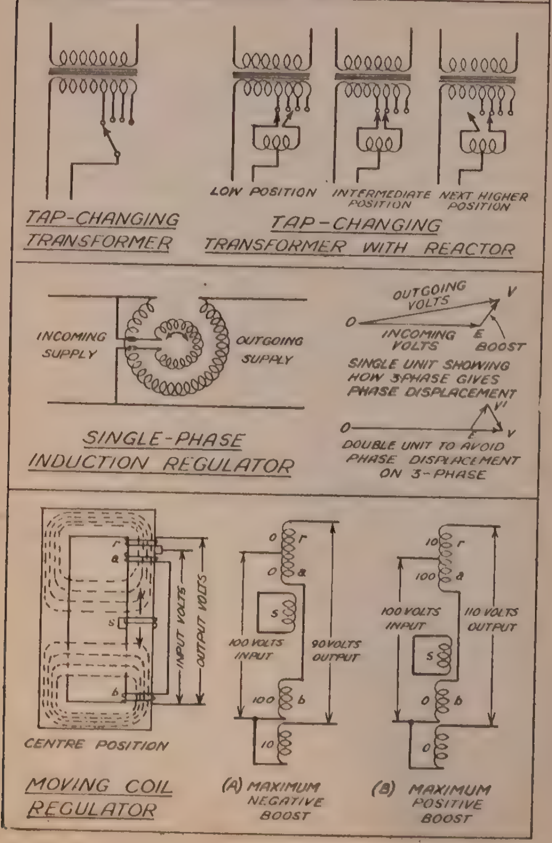
Where the load must not be interrupted various methods are used, such as two parallel windings or the use of a reactor to bridge the change-over. In the former case two equal and parallel windings are used on the tap-changing side and the whole load is switched over to one half-winding while the tapping is changed on the other half. This is a rather expensive system of construction and the reactor system more usually used.

As shown in the diagram, a reactor can be used to bridge two tapping so that a change-over can be made. The supply is connected to the centre of the reactor and the three stages are shown in the diagram. The system is similar to the use of a resistance for the temporary shorting of the end cells of a stationary battery on a battery-charging board.

The reactor system has proved satisfactory for all sizes of tap-changing transformers from 1 to 2 kilowatts for isolated lines supplying farms, etc., in rural districts to the 60,000 kilovolt-amperes units on the grid. In the large units motor-driven switchgear is controlled by remote control gear. In the small units mercury switches are used in some cases and these can be arranged for automatic operation controlled by relays which operate on a change of voltage or a change of current. For small distribution transformers current control has been found very successful as minor voltage fluctuations do not then cause excessive switching operations. For large units where automatic control is used, voltage control is general.

The tap-change is normally on the low-tension side of a transformer.

VOLTAGE REGULATING APPARATUS



The Moving-Coil Regulator.—This regulator has been developed by Messrs. Ferranti, Ltd., and obtains its boost by a short-circuited coil with connections as shown in the diagram. The amount of boost obtained depends on the position of the coil, and as with the induction regulator a smooth, infinitely variable variation is obtainable. Remote or automatic control is easily arranged and recent improvements in construction have enabled the manufacturers to reduce the size of the units considerably.

The essential features of the moving-coil regulator comprise a two-legged core as used in transformer construction with coils *a* and *b* mounted respectively at the top and bottom of one leg, and a short-circuited coil *s* which is free to move up and down the leg between coils *a* and *b*. These elements are shown in the diagram. The moving coil *s* is entirely isolated electrically, so that no flexible connections, slip-rings, or sliding contact are required. If a voltage be applied to coil *a* only, the resulting current will depend upon the impedance of this coil, which is determined by the position of the moving coil *s*. This coil may be looked upon as a gate preventing the passage of magnetic flux through it. The flux path is shown in dotted lines. The closer the moving coil is to coil *a*, the greater its short-circuiting effect, and, therefore, the lower the effective impedance of coil *a*. Hence, with the moving coil in the position shown in Fig. A, the impedance of coil *a* will be small and of coil *b* large. If a voltage be applied across these two coils connected in series, then the greater part of the voltage will appear across coil *b* and a small part only across coil *a*, as shown in the figure. With the moving coil at the bottom of the leg, as in Fig. B, the respective impedances of coils *a* and *b* are reversed, and the greater voltage will now appear across coil *a*.

The Induction Regulator.—This apparatus enables a smooth, infinitely variable voltage variation to be obtained. The unit is similar in design to an induction motor in which the stator carries the current and the rotor is connected across the line as shown in the diagram. The unit gives a transformer action and results in a positive or negative boost according to the relative position of the rotor which can be moved through nearly 360°.

Induction regulators can be arranged for either remote or automatic control. Their disadvantage lies in the cost, as owing to it having to carry the main current it is a large unit with a heavy weight of copper.

COMPARISON OF SYSTEMS

NEUTRAL IS TAKEN AS HALF-SIZE

NAME	DIAGRAM OF LEADS	GRAPHICAL REPRESENTATION	CURVES	EQUIVALENT WEIGHTS OF COMBINED CONDUCTORS FOR THE SAME PERCENTAGE LOSS AND THE SAME VOLTAGE PF = 1·0
C.C. 2-WIRE	a, a	V		100
C.C. 3-WIRE	a_1, $a_1 - a_2$, a_1	$2V$, V, V		31·25
SINGLE PHASE 2-WIRE	a, a	V		100
SINGLE PHASE 3-WIRE	a_1, $a_1 - a_2$ NEUTRAL, a_2	$2V$, V, V		31·25
TWO PHASE 4-WIRE	a, a, a, a, a, a	V, V		100
TWO PHASE 3-WIRE	$a\sqrt{2}$, a, a	V, $V\sqrt{2}$, V		85·3
THREE PHASE "MESH" (OR Δ)	a, a, a, $a\sqrt{3}$, $a\sqrt{3}$, $a\sqrt{3}$	V		75
THREE PHASE "STAR" (OR Y) (VOLTS GIVEN BETWEEN OUTERS)	a, a, a, a, a, a	V, $V/\sqrt{3}$		75
THREE PHASE 4-WIRE (VOLTS GIVEN BETWEEN OUTERS AND NEUTRAL)	a_1, a, $a_1 + a_2 + a_3 = 0$ NEUTRAL, a, a, a_2, a_3	$V\sqrt{3}$, V		29·2

They are very successful for high-voltage testing plants and in this case the regulator is placed on the low-tension side of the step-up transformer. Any voltage from zero to the maximum can be obtained and the voltage can be raised gradually until the article under test breaks down.

With three single units on three-phase there is an inevitable phase displacement as shown in the diagram, but where this is a disadvantage twin units in series are used, and as shown this phase displacement is corrected. There is no phase displacement for single-phase.

EFFICIENCY OF SYSTEMS OF TRANSMISSION AND DISTRIBUTION

The normal method of comparing the efficiency of any transmission or distribution system is to compare the weight of copper required to transmit a certain load at a given voltage with the sum loss in transmission. For this purpose C.C. 2-wire is often taken as a standard and the other systems compared with it as regards the total weight of copper necessary.

Referring to the diagram opposite, the C.C. 2-wire system is taken as 100 per cent. and the weight of copper required is indicated for each different system. In these comparisons the power factor of an A.C. load is taken as unity and it is assumed that in a 2-, 3- and 4-wire system the loads are balanced. It will be seen that the three-phase 4-wire system scores in that a less total weight of copper is required than for any of the other systems illustrated.

Size of Neutral.—In the 3- and 4-wire systems employing a neutral, the size of the neutral conductor can be either equal to the "outers" or half the size of the "outers." For the calculations on the following page the neutral has been taken as half-size, and for cases where the neutral is full size allowance must be made for the increase in weight of copper. If a full-size neutral is used for a three-phase 4-wire system the total weight of copper is increased by one-seventh, making the comparative figure 33·4 per cent. compared with C.C. 2-wire.

DETAILS OF BRITISH STANDARD CONDUCTORS (SOLID AND STRANDED CIRCULAR)

No. and Diameter of Wires comprising Conductor.	Sectional Area of Conductor.			Diameter of each Wire in strand.		Standard Weight of Conductor. Per 1,000 yds.	Maximum Resistance at 60° F.	
	Nominal Area.	Calculated Area.					Plain Wires. Per 1,000 yds.	Tinned Wires. Per 1,000 yds.
Inch.	Sq. In.	Sq. In.	Sq. Mm.	Inch.	Mm.	Lbs.	Ohms.	Ohms.
1/·036	0·0010	0·001018	0·66	0·036	0·91	11·77	24·29	24·53
1/·044	0·0015	0·001521	0·98	0·044	1·12	17·58	16·26	16·42
3/·029	0·0020	0·001943	1·25	0·029	0·74	23·37	12·61	12·85
3/·036	0·0030	0·002994	1·93	0·036	0·91	36·02	8·180	8·260
1/·064	0·0030	0·003217	2·08	0·064	1·63	37·20	7·687	7·761
7/·029	0·0045	0·004546	2·93	0·029	0·74	54·39	5·387	5·493
7/·036	0·0070	0·007005	4·52	0·036	0·91	83·81	3·496	3·530
7/·044	0·0100	0·01046	6·75	0·044	1·12	125·2	2·340	2·363
7/·052	0·0145	0·01462	9·43	0·052	1·32	174·9	1·675	1·692
7/·064	0·0225	0·02214	14·30	0·064	1·63	264·9	1·106	1·117
19/·044	0·0300	0·02840	18·29	0·044	1·12	340·4	0·8637	0·8721
19/·052	0·0400	0·03960	25·5	0·052	1·32	475·5	0·6184	0·6244
19/·064	0·0600	0·06000	38·7	0·064	1·63	720·3	0·4082	0·4122
19/·072	0·0750	0·07592	49·0	0·072	1·83	911·6	0·3225	0·3257
19/·083	0·1000	0·1009	65·1	0·083	2·11	1,211	0·2427	0·2451
37/·064	0·1200	0·1168	75·4	0·064	1·63	1,403	0·2097	0·2118
37/·072	0·1500	0·1478	95·4	0·072	1·83	1,776	0·1657	0·1673
37/·083	0·2000	0·1964	127	0·083	2·11	2,360	0·1247	0·1259
37/·093	0·2500	0·2465	159	0·093	2·36	2,963	0·09933	0·1003
37/·103	0·3000	0·3024	195	0·103	2·62	3,635	0·08098	0·08177
61/·093	0·4000	0·4064	262	0·093	2·36	4,886	0·06026	0·06085
61/·103	0·5000	0·4985	322	0·103	2·62	5,994	0·04913	0·04961
91/·093	0·6000	0·6062	391	0·093	2·36	7,290	0·04040	0·04079
91/·103	0·7500	0·7435	480	0·103	2·62	8,942	0·03294	0·03326
127/·093	0·8500	0·8459	546	0·093	2·36	10,175	0·02895	0·02924
127/·103	1·0000	1·0376	669	0·103	2·62	12,481	0·02360	0·02383

DETAILS OF BRITISH STANDARD COPPER CONDUCTORS (SINGLE CONDUCTORS)

Diameter at 60° F.			Calculated Area.	Weight per 1,000 yds.			Resistance per 1,000 yds. at 60° F.			Dia. at 60° F.
Standard.	Min. Allowable.	Max. Allowable.		Standard.	Min. Allowable.	Max. Allowable.	Standard.	Max. allowable for Plain Wires.	Max. allowable for Tinned Wires.	Standard.
Inch.	Inch.	Inch.	Sq. In.	Lbs.	Lbs.	Lbs.	Ohms.	Ohms.	Ohms.	Inch.
0·0076	0·007485	0·007713	0·00004536	0·5246	0·5089	0·5404	529·20	545·10	555·70	0·0076
0·0100	0·009849	0·010150	0·00007854	0·9083	0·8810	0·9355	305·70	314·90	321·00	0·0100
0·0120	0·011820	0·012180	0·00011310	1·3080	1·2690	1·3470	212·30	218·60	222·90	0·0120
0·0180	0·01773	0·01827	0·0002545	2·943	2·855	3·031	94·35	97·18	99·06	0·0180
0·0290	0·02856	0·02943	0·0006605	7·639	7·410	7·868	36·35	37·44	38·16	0·0290
0·0360	0·03546	0·03654	0·0010180	11·770	11·420	12·120	23·59	24·29	24·53	0·0360
0·0440	0·04333	0·04466	0·001521	17·58	17·06	18·11	15·790	16·260	16·420	0·0440
0·0520	0·05121	0·05277	0·002124	24·56	23·82	25·30	11·300	11·640	11·760	0·0520
0·0640	0·06303	0·06495	0·003217	37·20	36·09	38·32	7·463	7·687	7·671	0·0640
0·0720	0·07091	0·07307	0·004072	47·09	45·67	48·50	5·897	6·074	6·133	0·0720
0·0830	0·08175	0·08424	0·005411	62·57	60·70	64·45	4·437	4·570	4·615	0·0830
0 0930	0·09159	0·09438	0·006793	78·56	76·20	80·92	3·534	3·640	3·676	0·0930
0·1030	0·10140	0·10450	0·008332	96·36	93·47	99·25	2·881	2·968	2·996	0·1030

COMPARISON OF OLD AND NEW CONDUCTOR SIZES

Although they are now seldom used, the old gauge numbers may be quoted, and this table enables the appropriate new size to be chosen.

New Standard.		Old Standard.	
New Nom. Area in Sq. In.	Number and Diameter in In. of Wires comprising Conductor.	Number and Gauge or Diameter in In. of Wires in Conductor.	Old Nom. Area in Sq. In.
0·0010	1/·036	1/20 S.W.G.	0·0010
0·0015	1/·044	—	—
—	—	1/18 ,,	0·0018
—	—	3/22 ,,	0·0018
0·0020	3/·029	—	—
—	—	7/25 ,,	0·0022
0·0030	3/·036	3/20 ,,	0·0030
—	—	7/23 ,,	0·0031
0·0030	1/·064	1/16 ,,	0·0032
—	—	7/22 ,,	0·0042
0·0045	7/·029	—	—
—	—	7/21½ ,,	0·0049
0·0070	7/·036	7/20 ,,	0·0070
—	—	7/19 ,,	0·0086
0·0100	7/·044	—	—
—	—	7/18 ,,	0·0125
0·0145	7/·052	—	—
—	—	7/17 ,,	0·0170
0·0225	7/·064	7/16 ,,	0·0220
0·0300	19/·044	—	—
—	—	19/18 ,,	0·0340
—	—	7/14 ,,	0·0350
0·0400	19/·052	—	—
—	—	19/17 ,,	0·0460
0·0600	19/·064	19/16 ,,	0·0600
0·0750	19/·072	19/15 ,,	0·0750
—	—	19/14 ,,	0·0940
0·1000	19/·083	—	—
0·1200	37/·064	37/16 ,,	0·1170
—	—	19/13 ,,	0·1250
0·1500	37/·072	37/15 ,,	0·1500
—	—	37/14 ,,	0·1820
0·2000	37/·083	37/·083"	0·2000
0·2500	37/·093	37/·092"	0·2500
0·3000	37/·103	37/·104"	0·3000
0·4000	61/·093	61/·092"	0·4000
0·5000	61/·103	61/·104"	0·5000
0·6000	91/·093	61/·112"	0·6000
0·7500	91/·103	91/·101"	0·7500
0·8500	127/·093	—	—
1·0000	127/·103	127/·101"	1·0000

FUSE WIRE TABLE

Current Rating of Fuse.	Tinned Copper Wire.		Standard Alloy* Wire.	
	Diameter (in.)	S.W.B.	Diameter (in.)	S.W.G.
1.	2.	3.	4.	5.
amperes.				
1·8	—	—	0·0164	27
3·0	0·006	38	0·024	23
5·0	0·0084	35	0·032	21
8·5	0·0124	30	—	—
10·0	0·0136	29	—	—
15·0	0·020	25	—	—
17	0·022	24	—	—
20	0·024	23	—	—
24	0·028	22	—	—
30	0·032	21	—	—
37	0·040	19	—	—
46	0·048	18	—	—
53	0·048	18	—	—
60	0·056	17	—	—
64	0·056	17	—	—
83	0·072	15	—	—
100	0·080	14	—	—

NOTE.—The current ratings given refer to the normal maximum current of the circuit and do not refer to the overload at which the fuse will operate.

The values of the currents are approximately those necessary to comply with British Standard Specification No. 88 applied to the above fuse-elements used in semi-enclosed fuses. Where fuses are known to conform to this Specification the size stated by the manufacturer on the case of the fuse should be adhered to in preference to that given in the Table, if the fuse is loaded to its full capacity.

* The term " Standard alloy " refers to the eutectic tin-lead alloy (63 per cent. tin, 37 per cent. lead).

From I.E.E. " Regulations for the Electrical Equipment of Buildings," Eleventh Edition (June 1939).

Extract from the " Regulations for the Electrical Equipment of Buildings." Eleventh Edition (June, 1939).

CURRENT RATING OF CABLES.

Current Rating for **Vulcanized-Rubber-Insulated Cables*** *run :*

(i) *Bunched, and enclosed in one conduit, troughing, or casing (Cols. 3 and 4 or Col. 7 according to the type and number so run) ;*

(ii) *Bunched, and open (Cols. 3 and 4 or Col. 7 according to the type and number so run).*

Conductor.		Not more than Two Single-Core Cables.†				Not more than Four Single-Core Cables, or Two Twin Cables, or One Concentric Cable.		
		Current Rating (subject to Voltage Drop).		**Approximate Length in** Circuit (*Lead plus Return*) for 1-volt Drop with Current Rating in Col. 3 **or Col. 4.**		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 7.	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	D.C.	Single-phase A.C.	D.C.	Single-phase A.C.	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return*, for D.C.	***Lead plus Return***, for Single-phase A.C. : *Lead only*, for **balanced 3-phase** A.C.
1.	2.	3.	4.	5.	6.	7.	8.	9.
Sq. in.		Amps.	Amps.	Feet.	Feet.	Amps.	Feet.	Feet.
0·007	7/·036	29	29	27	27	23	34	34
0·01	7/·044	38	38	32	32	30	41	41
0·0145	7/·052	45	45	37	37	36	46	46
0·0225	7/·064	56	56	45	45	45	57	57
0·03	19/·044	65	65	50	49	52	61	61
0·04	19/·052	78	78	58	57	62	73	73

0·06	19/·064	102	102	67	65	82	84	84
0·1	19/·083	147	147	79	74	118	98	96
0·15	37/·072	189	189	90	78	151.	113	103
0·2	37/·083	229	229	99	79	183	124	103
0·3	37/·103	298	298	117	78	238	146	103
0·4	61/·093	358	358	130	72	286	162	96
0·5	61/·103	413	413	138	66	330	173	86
0·75	91/·103	575	530	149	65	—	—	—
1·0	127/·103	740	648	161	47	—	—	—

NOTE.—The Table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used. (Braided vulcanized-rubber-insulated cables run open are required under Regulation 402 to be spaced on insulators.)

The Table refers to situations where the ambient air temperature does not exceed 90° F. (32·2° C.). Where the ambient air temperature is abnormally high the current ratings given in the Table shall be multiplied, and the lengths for 1-volt drop divided, by the appropriate factor as follows :

Ambient air temperature	95° F.	100° F.	105° F.	110° F.	115° F.
Factor	0·90	0·80	0·69	0·55	0·38

The current ratings in the table are subject to the maximum permissible voltage drop (see Regulation 304) not being exceeded.

* Including tough-rubber-protected cables and lead-covered cables, but excluding (for use with alternating current) such of the following cables as are prohibited under Regulation 308 :

(a) Single-core armoured or ferrous-sheathed cables.
(b) Single-core cables above 0·1 sq. in. encased in brass, copper, etc.

† For one twin cable, see Columns 7 to 9.

Extract from the "Regulations for the Electrical Equipment of Buildings." Eleventh Edition (June, 1939).

CURRENT RATING OF CABLES.

Current Rating for **Vulcanized-Rubber-Insulated Cables*** *run:*
(i) *Bunched, and enclosed in one conduit, troughing, or casing (Col. 3 or Col. 6 according to the type and number so run);*
(ii) *Bunched, and open (Col. 3 or Col. 6 according to the type and number so run).*

Conductor.		Not more than Six Single-Core Cables, or Three Twin Cables, or One Three-Core or Four-Core Cable, or Two Concentric Cables.			Not more than Ten Single-Core Cables, or Five Twin Cables, or Two Three-Core or Four-Core Cables, or Three Concentric Cables.		
		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 3.		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 6.	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return*, for D.C.	*Lead plus Return*, for Single-phase A.C.; *Lead only*, for balanced 3-phase A.C.	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return*, or D.C.	*Lead plus Return*, for Single-phase A.C.; *Lead only*, for balanced 3-phase A.C.
1.	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Sq. in.		Amps.	Feet.	Feet.	Amps.	Feet.	Feet.
0·007	7/·036	20	40	40	17	45	45
0·01	7/·044	27	45	45	23	54	54
0·0145	7/·052	32	52	52	27	61	61
0·0225	7/·064	39	65	65	34	76	76
0·03	19/·044	46	70	70	39	84	84
0·04	19/·052	55	82	82	47	95	95

0·06	19/·064	71	97	97	61	113	113
0·1	19/·083	103	113	110	[illegible]	131	129
0·15	37/·072	132	128	118	113	150	137
0·2	37/·083	160	142	[illegible]	—	—	—

Note.—The Table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used. (Braided vulcanized-rubber-insulated cables run open are required under Regulation 402 to be spaced on insulators.)

The Table refers to situations where the ambient air temperature does not exceed 90° F. (32·2° C.). Where the ambient air temperature is abnormally high, the current ratings given in the Table shall be multiplied, and the lengths for 1-volt drop divided, by the appropriate factor as follows:

Ambient air temperature	95° F.	100° F.	105° F.	110° F.	115° F.
Factor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The current ratings in the above table are subject to the maximum permissible voltage drop (see Regulation 204) not being exceeded.

* Including tough-rubber-protected cables and lead-covered cables, but excluding (for use with alternating current) such of the following cables as are prohibited under Regulation 205:

(a) Single-core armoured or ferrous-sheathed cables.
(b) Single-core cables above 0·1 sq. in. encased in brass, copper, etc.

Extract from the " Regulations for the Electrical Equipment of Buildings."
Eleventh Edition (June, 1939).
CURRENT RATING OF CABLES.

Current Rating (subject to Voltage Drop) for ***Vulcanized-Rubber-Insulated Cables**** *run :*
(i) *Bunched, and enclosed in one conduit, troughing, or casing (Col. 3 or Col. 5 according to the type and number so run);*
(ii) *Bunched, and open (Col. 3 or Col. 5 according to the type and number so run);*
(iii) *Separated, and open (Col. 3 only).*

Conductor.		Not more than Four Single-Core Cables, or Two Twin (or Concentric) Cables, or One Three-Core Cable.		Not more than Eight Single-Core Cables, or Four Twin (or Concentric) Cables, or Two Three-Core Cables.	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	Current Rating (subject to Voltage Drop), for D.C., or Single-phase or 3-phase A.C.	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 3 : *Lead Plus Return*, for D.C., or Single-phase A.C. ; *Lead only*, for balanced 3-phase A.C.	Current Rating (subject to Voltage Drop), for D.C., or Single-phase or 3-phase A.C.	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 5 : *Lead Plus Return*, for D.C., or Single-phase A.C. ; *Lead only*, for balanced 3-phase A.C.
1.	2.	3.	4.	5.	6.
Sq. in.		Amps.	Feet.	Amps.	Feet.
0·0015	1/·044	5	36	5	36
0·002	3/·029	5	47	5	47
0·003	3/·036	10	35	8†	42
0·0045	7/·029	15	34	12†	42

NOTE.—The Table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used. (Braided vulcanized-rubber-insulated cables run open are required under Regulation 402 to be spaced on insulators.)

In conditions of abnormally high ambient air temperature, the Notes to Table on the previous page should be consulted.

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

The current rating of fittings wire (3/·020 in. cable) is 3 amps.

* Including tough-rubber-protected cables and lead-covered cables, but excluding (for use with alternating current) single-core cables armoured with wire or tape of magnetic material and such ferrous-sheathed cables as are prohibited under Regulation 308.

† These figures (8 and 12) may be increased to 9 and 13·5 amperes respectively, where a diversity factor can properly be applied to the circuit which feeds the cables forming the group of final sub-circuits.

Size of Conduit.			½ in.		⅝ in.		¾ in.		1 in.		1¼ in.		1½ in.		2 in.		2½ in.	
Conductor of Cable.			Maximum Number of Cables.															
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	Approximate Overall Diameter of Cable.																
1.	2.	3.	4.		5.		6.		7.		8.		9.		10.		11.	
			S	B	S	B	S	B	S	B	S	B	S	B	S	B	S	B
Sq. in.		In.																
0·0015	1/.044	0·140	2	2	5	4	7	6	13	10	20	14	–		–	–	–	–
0·002	3/.029	0·172	–		4	3	7	5	12	10	20	14	–	–			–	–
0·003	3/.036	0·194	–	–	3	2	5	4	10	8	18	12	–	–	–		–	
0·0045	7/.029	0·205	–	–	2	2	5	4	8	6	12	10	–	–	–	–	–	–
0·007	7/.036	0·235	–	–	–	–	3	2	6	5	10	8		–		–		–
0·01	7/.044	0·263		–		–	2	–	5	4	8	7		–		–		–
0·0145	7/.052	0·287	–	–	–	–	2	–	4	3	6	5	8	6	–	–		–
0·0225	7/.064	0·342		–	–	–		–	3	2	4	4	7	6		–		–
0·03	19/.044	0·377	–		–	–		–	2	–	4	3	6	5	10	7	12	8
0·04	19/.052	0·428	–		–		–	–		–	3	2	5	4	8	6	9	7
0·06	19/.064	0·503	–	–	–	–	–	–	–	–	–	–	3	3	6	5	8	6
0·1	19/.083	0·645	–	–	–		–	–		–	–	–	–		4	3	5	4
0·15	37/.072	0·756	–	–	–	–	–	–	–	–	–	–	–	–	2	2	3	2

NOTE.—This Table shows the capacity of conduits for the simultaneous drawing-in of cables. The Table applies to 250-volt grade vulcanized-rubber-insulated cables conforming in all respects to British Standard Specification No. 7, and the maximum numbers of cables shown in the Table apply to all types of conduits irrespective of whether they are light gauge or heavy gauge.

The columns headed S apply to runs of conduit which have a distance not exceeding 14 ft. between draw-in boxes, and which do not deflect from the straight by an angle of more than 15°.

The columns headed B apply to runs of conduit which deflect from the straight by an angle of more than 15°.

MOTORS

Direct Current.—D.C. motors are divided into three classes, as follows :

(1) *The series-wound motor*, in which the field is in series with the armature. This type of motor is only used for direct coupling and other work where the load (or part of the load) is permanently coupled to the motor. This will be seen from the speed-torque characteristic, which shows that on no load or light load the speed will be very high and therefore dangerous.

(2) *The shunt-wound motor.*—In this case the field is in parallel with the armature, as shown in the diagram, and the shunt motor is the standard type of D.C. motor for ordinary purposes. Its speed is nearly constant, falling off as the load increases due to resistance drop and armature reaction.

(3) *The compound-wound motor*, which is a combination of the two. There is a series winding in series with the armature and a shunt winding in parallel with it. The relative proportion of the field and series winding can be varied in order to make the characteristics nearer those of the series motor or those of the shunt-wound motor. The typical speed-torque curve is shown in the diagram.

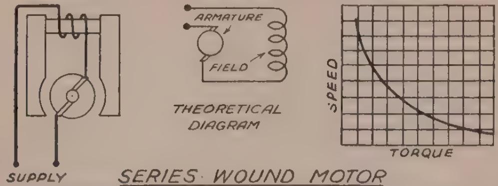
Compound-wound motors are used for cranes and other heavy duty where an overload may have to be carried and a heavy starting torque is required.

Speed Control.—Speed control is obtained as follows :

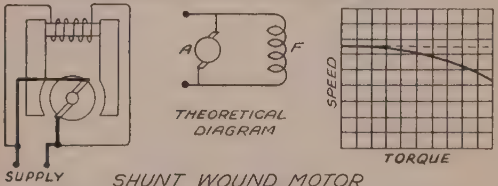
Series motors, by series resistance in series with the armature and the field winding of the motor. This is the method used in traction, e.g. tramcars, but in this case additional variation is obtained by starting up two motors in series and then connecting them in parallel when a certain speed has been reached.

Shunt- and Compound-wound Motors.—Speed regulation on shunt- and compound-wound motors is obtained by resistance in series with the shunt-field winding only. This is shown diagrammatically in the page of diagrams.

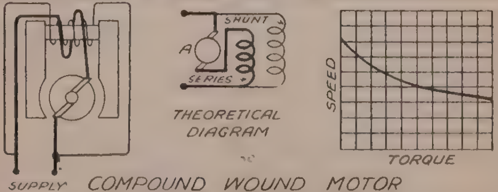
D. C. MOTORS



SERIES WOUND MOTOR



SHUNT WOUND MOTOR



COMPOUND WOUND MOTOR

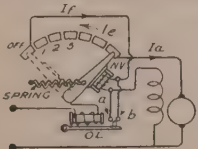
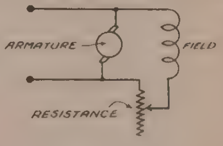


DIAGRAM OF FACE PLATE STARTER FOR SHUNT MOTOR



SPEED CONTROL OF SHUNT MOTOR BY FIELD RHEOSTAT

Starting.—The principle of starting these motors will be seen from the diagram showing the face-plate type starter in the sketch (page 139), the starting resistance being in between the segments marked 1, 2, 3, etc.

The starting-handle is held in position by the no-volt coil, marked NV, which automatically allows the starter to return to the off position if the supply fails. Overload protection is obtained by means of the overload coil, marked OL, which on overload short circuits the no-volt coil by means of the contact marked *a* and *b*.

When starting a shunt-wound motor it is most important to see that the shunt rheostat (or speed control) is in the slow-speed position. This is because the starting torque is proportional to the field current and this field current must be at its maximum value for starting purposes. Many starters have the speed regulator interlocked with the starting-handle so that the motor cannot be started with a weak field.

A.C. MOTORS

Alternating current motors can be grouped as follows:

(*a*) Induction motors.
(*b*) Synchronous motors.
(*c*) Variable-speed commutator motors.
(*d*) Series motors.
(*e*) Repulsion and shunt motors.

The first three are used in all sizes and for all general purposes induction motors are employed on account of their simplicity, reliability and low first cost. Synchronous motors are generally installed where it is desirable to obtain power-factor improvement or where a constant speed is required. They are only economical in the case of loads of 50 h.p. and over, although there are instances where smaller machines are in use for special purposes.

The three-phase commutator motor is the only A.C. motor for large outputs which gives full speed control, and although expensive it is now being used to an increasing extent for duties where variable speed is required.

The last two groups represent the types used for small or fractional h.p. motors, which also include induction motors.

THE INDUCTION MOTOR

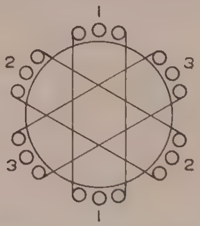


FIG. 1 THREE-PHASE STATOR WINDING
TO PRODUCE ROTATING FIELD

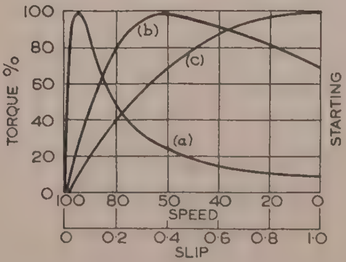


FIG. 2 TORQUE-SLIP CURVES

(A) = NO ADDED RESISTANCE IN ROTOR R = 1
(B) = WITH ADDED RESISTANCE R = 4
(C) = WITH MORE ADDED RESISTANCE R = 20

These small motors have been developed to a great extent during the last few years on account of the number of small machines which incorporate individual drive. Normally fractional h.p. motors include machines developing from $\frac{1}{40}$ h.p. to about 2 h.p., although this latter size appears not to fit in with the term fractional h.p. The reason for its inclusion is that a different technique is used for manufacturing small motors which are turned out in large quantities by mass-production methods. Most of the manufacturers of these small motors can supply them with gearing incorporated giving final shaft speed of any value down to one revolution in 24 hours.

The induction motor, which can be termed our standard motor, is now made on repetition lines, and as a result of the recent standardization of voltage and frequency, the cost of standard-sized new motors is exceptionally low. The absence of a commutator and, in the case of the squirrel-cage motor, of any connection whatever to the rotor, combined with the simplicity of starting, make it the most reliable and the cheapest form of power available.

There are a number of specialized motors which are used in a few special applications, but these will not be described as they are really rather of academic interest than of general use in industry.

The use of synchronous motors for improvement of power factor is referred to in the section dealing with power factor, but it should be realized that the essential points of a synchronous motor are its constant speed (depending on the frequency) and the fact that the power factor at which it operates can be varied at will over a certain range – usually from 0·6 leading to 0·8 lagging—this being accomplished by varying the exciting current.

THE INDUCTION MOTOR

The essential principle of an induction motor is that the current in the stator winding produces a rotating flux which induces a current in the winding of the rotor, thus producing the necessary torque.

The stator winding to produce this rotating torque is fairly simple in the case of a three-phase motor, being based on three symmetrical windings, as shown in Fig. 1. In the case

of single-phase and the now vanishing two-phase it is not quite so easily understood.

The rotating flux is bound to "cut" the rotor winding if this is stationary and thereby induces a current in it, thus producing the torque required to run the rotor.

The rotating field will revolve at synchronous speed and if no power whatever was required to rotate the rotor it would catch up with the flux and would also revolve at synchronous speed. As, however, a certain amount of power is required to rotate the rotor even if unconnected to any load, the speed is always slightly less than synchronous. As the load increases the speed falls in order to allow the additional rotor currents to be induced.

The difference between the actual speed and synchronous speed is termed the *slip*, which is usually expressed as a percentage or a fraction of the synchronous speed. For standard machines the maximum slip at full load is usually about 4 per cent.

Calculation of Synchronous Speed.—Induction motors are made with any number of poles (in multiples of 2), but it is not usual to make motors with more than 10 poles, and for ordinary use 2, 4 and 6 poles are chosen, if possible, on account of the lower first cost and higher efficiency.

Synchronous speed is given by

$$\text{synchronous speed in r.p.m.} = \frac{\text{frequency} \times 60}{\text{number of pairs of poles}}.$$

Thus a 2-pole motor on 50 cycles will have a synchronous speed of 3,000 r.p.m., a 4-pole 1,500 r.p.m., and a 6-pole 1,000 r.p.m. The suitability of 1,500 r.p.m. for many purposes has made the 4-pole motor the more usual.

The actual rotor speed for 4 per cent. slip is given for various motors on 50 cycles in the table on page 150. Slip is calculated from

$$\text{percentage slip} = \frac{(\text{syn. speed} - \text{rotor speed}) \times 100}{\text{syn. speed}},$$

and the rotor speed for any given slip will be

$$\text{rotor speed} = \text{syn. speed}\left(\frac{100 - \text{slip}}{100}\right),$$

the slip being the percentage slip.

Variation of Slip with Torque.—It can be shown that the torque of an induction motor is proportional to

$$T = \frac{kE_2sR_2}{R_2^2 + (sX_2)^2}$$

where T = torque
k = constant
E_2 = rotor voltage
s = fractional slip
R_2 = rotor resistance
X_2 = rotor reactance.

The variation of slip with torque can therefore be calculated and typical torque-slip curves are given in Fig. 2. These curves are for the same motor and curve, (a) is for the rotor short-circuited, whereas (b) and (c) are for cases where additional or added resistance has been put in the rotor circuit. It will be seen from these curves and also from the formula above that the torque at starting or low speeds is greatly increased by adding resistance in the rotor circuit, and this principle is made use of in the wound-rotor induction motor which is used to start up against heavy loads.

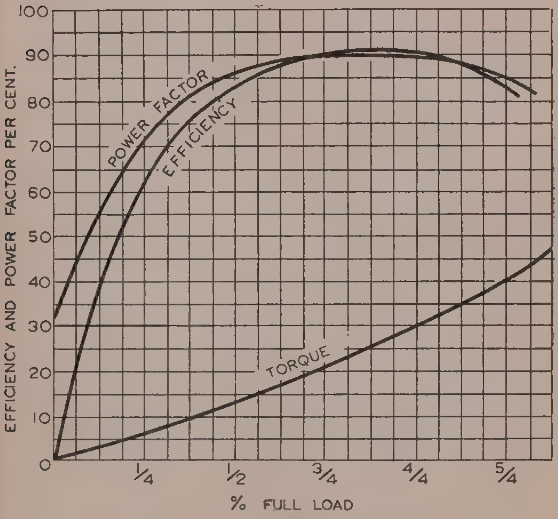
It can also be shown that maximum torque occurs when $R_2 = sX_2$ when the slip will be $s = \frac{R_2}{X_2}$.

Wound-rotor or Slip-ring Motor.—The slip-ring induction motor is used for duties where the motor has to start up against a fairly heavy load and the slip-rings are arranged for added resistance to be inserted in the rotor circuit for starting purposes. The diagram in Fig. 3 shows how the various circuits are connected to the supply and to the variable rotor resistance.

This type of motor is referred to as a *wound-rotor* motor, because for this purpose the rotor has to be wound with insulated conductors similar to those used for the stator. In the case of larger motors, an arrangement is fitted to the rotor shaft enabling the slip-rings to be short-circuited and the brushes lifted off the slip-rings, thus reducing both electrical and friction losses. Starters for these motors are described in the section on *Motor Starters*.

Squirrel-Cage Motors.—When motors do not have to start up against any real load, squirrel-cage motors are used. These are so termed on account of the fact that the construc-

INDUCTION MOTOR PERFORMANCE



Graph showing variation of power-factor and efficiency with load. Note that maximum values occur between three-quarters and full load.

STARTING INDUCTION MOTORS

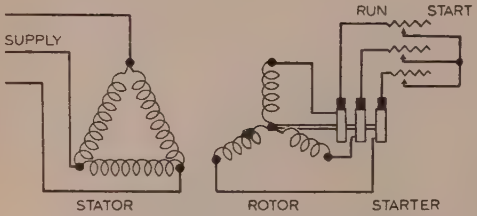


FIG. 3 STARTING WOUND-ROTOR MOTOR

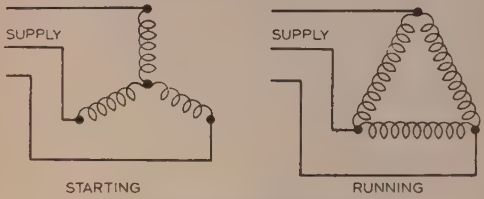


FIG. 4 STAR-DELTA STARTING FOR SQUIRREL-CAGE MOTORS

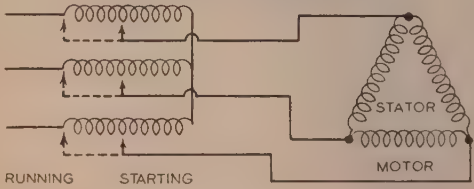


FIG. 5 AUTO-TRANSFORMER STARTING FOR SQUIRREL-CAGE MOTORS

tion of the rotor circuit is similar to a revolving cage used for tame squirrels. The circuit consists of solid bars of copper arranged round the periphery of the rotor and connected at each end by a ring of copper. The resistance of the rotor is thus low and very little starting torque is available. On the other hand, a very cheap and efficient motor is produced.

Squirrel-cage induction motors may be started either

(*a*) by " direct-on " switching ;
(*b*) by Star-delta connections ;
(*c*) by use of an auto-transformer.

The use of direct-on starting (*a*) is limited to motors below a certain size—the limit varying according to the rules of the Supply Authority. This varies from 2 h.p. to 5 h.p.

Star-delta starting is the most usual method of starting and consists of connecting the stator winding in star until a certain speed has been reached, when it is switched over to delta, the circuit connections being as shown in Fig. 4. By this means the voltage on the stator is reduced to one-third of the supply and the starting current is thus limited in the same ratio. The star connection also means that at starting the line current is also one-third of the phase current and thus the actual line current at starting is only one-third of what it would be if switched on direct. The torque is naturally reduced in the same proportion, so that this method can only be used where the starting load is small.

The use of an auto-transformer is confined to those cases where a definite limit is required to the starting current, and the arrangement is shown in Fig. 5. By suitable arrangement of the transformer tapping for starting a certain starting torque can be provided if this does not result in excessive starting current. The diagram in Fig. 5 is only diagrammatical, as the auto-transformer is disconnected from the supply in the running position.

Direction of Rotation.—In order to reverse the direction of rotation of a three-phase induction motor, two only of the three leads to the stator must be interchanged. In the case of a new motor the direction can be checked by a trial and then two of the leads changed over if necessary.

In the case of reversing motors, this change is obtained by means of alternative stator switches on the starting panel.

FULL LOAD CURRENTS ALTERNATING CURRENT MOTORS

The values given below may vary slightly with different types of motors but can be accepted as reasonably accurate.

B.H.P.	In Amperes.																	
	Single Phase.										Two Phase.		Three Phase.					
	Split Phase.					Capacitor.												
	Volts.					Volts.					Volts.		Volts.					
	100	200	230	400	480	100	200	230	400	480	200	400	200	220	350	400	440	500
1	12·9	6·5	5·6	3·2	2·7	11·6	5·9	5·1	2·9	2·4	2·9	1·4	3·4	3·1	2	1·7	1·5	1·4
2	24	12	10·4	6	5	22	11	9·5	5·4	4·5	5·7	2·9	6·6	6	3·8	3·3	3	2·6
3	35	17	15	9	7	31	15	13	7·8	6·7	8·4	4·2	9·8	8·9	5·7	4·9	4·5	3·9
4	45	23	20	11	9·4	40	20	18	10	8·5	11	5·6	13	12	7·5	6·5	6	5·2
5	56	28	25	14	12	51	25	22	13	11	14	6·8	16	14	9·1	7·9	7·2	6·3
6	66	33	29	17	14	60	29	26	15	13	16	8·1	19	17	11	9·4	8·5	7·5
7½	82	41	36	21	17	74	37	33	19	15	20	10	24	21	14	12	11	9·4
8	87	43	38	22	18	78	39	34	20	16	21	11	25	22	15	13	12	9·8
10	109	54	47	27	23	98	48	42	24	20	26	13	30	27	17	15	14	12
15	159	79	69	40	33	147	73	64	37	31	38	19	44	40	26	22	20	18
20	209	105	91	52	44	193	97	84	48	41	50	25	58	53	34	29	26	23
25	256	128	111	64	53	237	118	103	59	49	62	31	72	66	42	36	33	29
30	306	152	134	77	64	283	142	124	71	59	74	37	86	78	50	43	39	34
40	400	200	174	100	83	370	185	161	93	77	96	48	111	101	64	56	51	45
50	487	244	212	122	102	450	226	196	113	94	118	59	137	124	79	68	62	55
60	586	292	254	147	122	542	270	235	136	113	140	70	162	147	94	81	74	65
75	715	358	310	179	150	662	330	287	166	139	171	86	198	180	114	99	90	79
100	941	471	410	235	196	870	435	380	217	182	228	114	263	239	152	132	120	105
150	—	—	—	—	—	—	—	—	—	—	336	168	388	356	225	194	176	155
200	—	—	—	—	—	—	—	—	—	—	446	223	517	468	299	258	235	207

The current required for any Alternating Current Motor can be obtained from the following equations. The Power Factor and Efficiency can be obtained from the table given on page 150.

Single Phase

$$\text{Current} = \frac{\text{Horse-power} \times 74{,}600}{\text{Voltage} \times \text{Power Factor} \times \text{Efficiency}}$$

Three Phase

$$\text{Current} = \frac{\text{Horse-power} \times 74{,}600}{1{\cdot}732 \times \text{Voltage} \times \text{Power Factor} \times \text{Efficiency}}$$

Two Phase, four wire supply

$$\text{Current} = \frac{\text{Horse-power} \times 74{,}600}{2 \times \text{Voltage} \times \text{Power Factor} \times \text{Efficiency}}$$

Two Phase, three-wire supply

Current = In Outers, as above.

In Common ,1·414 × Outer Value

SYNCHRONOUS MOTORS

The synchronous motor is essentially a reversed alternator and is specifically used for power factor correction. As its name implies, it has a constant speed (running at synchronous speed at all loads), and its power factor can be controlled by varying the exciting current. It can thus be made to take a leading current for power factor improvement purposes. The synchronous motor itself is not self-starting and it must also be synchronized on to the supply when it has been run up to speed by a special starting motor or by some other means.

If the motor is seriously overloaded it falls out of step and the normal starting and synchronizing operations must be followed through again. For industrial purposes, however, the *synchronous-induction motor* has been developed in order to combine the starting and overload properties of the slip-ring induction-motor with the advantage of a current at a leading power factor which is the essential value of the synchronous motor.

There are two methods by which this combination is obtained—*a salient-pole synchronous motor* may be fitted with a squirrel-cage winding in its rotor so that the machine may start as an induction motor. The other arrangement is to connect the rotor of a slip-ring induction-motor to a D.C. exciter as soon as full speed is reached. This latter arrangement is generally referred to as the synchronous-induction motor and has been developed for industrial purposes in sizes mainly above 50 h.p. This machine usually has a direct coupled D.C. exciter and up to full load starting torque can be obtained with approximately 25 per cent. more than full-load current and a pull-out torque of $2\frac{1}{2}$–3 times full-load torque is obtainable since on overload the machine reverts to an induction motor.

The load which it will carry as a synchronous motor depends upon the power factor at which it is working and for a leading power factor $1\frac{1}{2}$–$1\frac{3}{4}$ times full-load torque is its normal limit as a synchronous motor.

Some very neat synchronous induction motors have been produced for industrial purposes, but they can only be used successfully on a fairly constant load running for reasonably long periods.

For intermittent use the advantage of power factor improvement is reduced, so that the extra cost of this type of motor is not warranted.

SYNCHRONOUS SPEED

No. of Poles on Stator.	Synchronous speed on 50 ~ r.p.m.	Rotor Speed at 4 per cent. Slip.
2	3,000	2,880
4	1,500	1,440
6	1,000	960
8	750	720
10	600	576

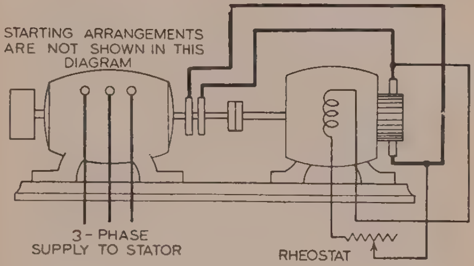
EFFICIENCY AND POWER FACTOR OF 4-POLE INDUCTION MOTORS ON 50 CYCLES

The following are average values for standard motors running at 1,440 to 1,470 r.p.m.

FULL LOAD

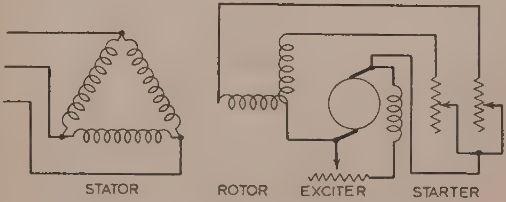
H.P.	Efficiency.				Power Factor.			
	Single Phase.		Two Phase.	Three Phase.	Single Phase.		Two Phase.	Three Phase.
	Split Phase.	Capacitor.			Split Phase.	Capacitor.		
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
1	65	70	73	74	0·80	0·90	0·79	0·81
1½	69	74	76	78	0·81	0·90	0·79	0·81
2	72	76	78	80	0·82	0·91	0·82	0·84
3	74	78	82	83	0·82	0·92	0·82	0·84
4	76	80	83	84	0·82	0·93	0·82	0·84
5	78	82	84	85	0·83	0·93	0·84	0·86
7½	81	83	85	86	0·84	0·94	0·85	0·87
10	81	84	87	88	0·84	0·94	0·86	0·88
12½	81	84	87	88	0·84	0·90	0·86	0·88
15	82	85	88	88	0·85	0·90	0·87	0·89
20	83	86	88	90	0·85	0·90	0·88	0·90
30	84	87	89	90	0·86	0·90	0·88	0·90
40	84	88	90	90	0·86	0·90	0·89	0·90
50	85	88	91	91	0·87	0·91	0·90	0·91
75	86	89	91	91	0·87	0·93	0·90	0·91
100	86	90	92	92	0·88	0·94	0·91	0·92

SYNCHRONOUS MOTORS



MOTOR WITH EXCITER

POWER FACTOR IS CONTROLLED BY RHEOSTAT IN EXCITING CIRCUIT OF EXCITER



SYNCHRONOUS INDUCTION MOTOR

A TWO-PHASE ROTOR IS USED. DIAGRAM SHOWS METHOD OF STARTING AS AN INDUCTION MOTOR

"Straight" Self-contained Motor.—The top drawing shows the arrangement of a self-contained synchronous motor suitable for driving a steady load but does not show any method of starting. The three-phase supply is taken direct to the stator and a D.C. supply is necessary for excitation. This can either be obtained from a separate D.C. system (sometimes used where there are several motors in use) or from the individual exciter mounted direct to the motor as shown. Power-factor control is obtained by varying the excitation—this being controlled in large motors by means of a rheostat in the exciting circuit of the exciter.

A "straight" synchronous motor is not self-starting and must be started by an auxiliary motor. This is usually an induction motor mounted on the common shaft. After the required speed has been obtained the motor is switched in by synchronizing in a similar manner to an alternator. While it is being driven by the auxiliary motor it is in all respects an alternator.

This type of motor in its simple form has no starting torque and will not therefore start up under load. Also if the overload capacity is exceeded the motor will fall "out of step" and will shut down. It must then be started up and synchronized in the usual manner.

Synchronous-Induction Motor.—The diagram for a typical self-starting synchronous-induction motor is shown in the lower diagram. It will be seen that by means of a starting resistance the machine will start up as an induction motor. As full speed is reached the motor will pull into synchronism (against full load if required) and the starting resistances are then short-circuited.

A two-phase winding is used on the rotor and arranged so that the neutral point is used as one connection for the exciting circuit.

Hunting.—One of the features of a synchronous motor is that on a fluctuating load it may *hunt*. This is also known as phase swinging and takes the form of oscillations or fluctuations in the speed of the motor. If these reach a certain magnitude the motor must fall out of step.

In modern industrial motors this is prevented by means of a damping winding in which eddy currents are induced by the variations in speed should hunting occur.

Hunting is more likely to occur with weak excitation than with strong. Temporary hunting can therefore often be cured by strengthening the field.

SINGLE-PHASE MOTORS

Single-phase motors are only made in small sizes, as for ordinary use three-phase motors are preferable and are required by the supply authority for loads over a few horsepower.

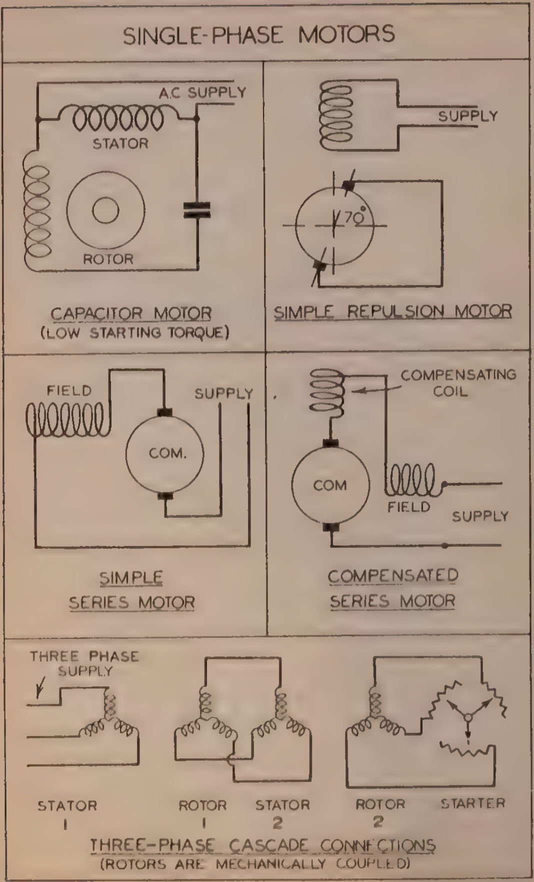
Single-phase Induction Motors.—If a three-phase motor which is running has two of its phases disconnected it will still run and will then be equivalent to a single-phase motor. It will not, however, start up as a single-phase motor, and it is in this respect that single-phase motors are of one or more special types.

Split-phase Starting.—The single winding of a single-phase stator will not produce a rotating field by itself and some arrangement is required to turn the alternating field which it produces into a rotating field. One method of providing this is to have a second winding on the stator and to alter the phase of the current in the second winding, thus making it similar to a two-phase motor. The phase displacement may be obtained by connecting a resistance in series with the starting winding, or shunting one winding by a resistance while the other is shunted by an inductance.

The starting winding is only put into circuit for starting the motor up and is cut out as soon as the requisite speed has been reached. Only a fairly small starting torque is obtained by this method.

Capacitor Motor.—Instead of using inductance or resistance for giving the necessary phase displacement in the starting winding a condenser may be used as in the capacitor motor. This has certain advantages in that the starting winding is left in circuit all the time, there being no low power factor due to the inductance of this circuit. The motor thus runs continuously in many respects as a two-phase motor.

The capacitor motor has a larger starting torque than the split-phase type, and in many cases an extra large capacity condenser is used for starting—a smaller one being left in circuit for running. The power factor will naturally also be higher.


SINGLE-PHASE MOTORS
A.C SUPPLY
STATOR
ROTOR
CAPACITOR MOTOR
(LOW STARTING TORQUE)
SUPPLY
70°
SIMPLE REPULSION MOTOR
FIELD
SUPPLY
COM.
SIMPLE
SERIES MOTOR
COMPENSATING
COIL
COM
FIELD
SUPPLY
COMPENSATED
SERIES MOTOR
THREE PHASE
SUPPLY
STATOR
1
ROTOR
1
STATOR
2
ROTOR
2
STARTER
THREE-PHASE CASCADE CONNECTIONS
(ROTORS ARE MECHANICALLY COUPLED)

Single-phase Series Motor.—A motor constructed somewhat differently but connected in the same way as a D.C. series motor will run satisfactorily, and this type is sometimes used for single-phase traction work. The essential difference in construction is that the field system must be laminated to avoid iron losses with an alternating field and the stator winding should be similar to that of an induction motor.

In performance it is similar to the D.C. series motor and the speed decreases as the load increases. Unlike most A.C. motors, the power factor falls with the load and is highest on light loads.

Starting is usually arranged by means of an auto-transformer with variable tappings so that the motor is started on a reduced voltage and the pressure increased to normal as the speed rises.

In the *compensated series motor* an auxiliary field winding is connected in series with the field between the armature and the main field winding. This acts in the same way as the interpoles of a D.C. machine, neutralizing the cross-ampere turns. By this means the low power factor on load is improved.

Repulsion Motors.—There are many forms of repulsion motors, but the main principle is that a stator winding similar to a series motor is used with a wound rotor having a commutator which is short circuited. The brushes are set at an angle (about 70°), and by means of transformér action the field and armature fluxes are such that they repel each other and the rotor produces a torque.

Repulsion motors can be started either by a variable series resistance or by auto-transformer, and a fair starting torque can be obtained. On this account the principle is used for starting in the *repulsion-start single-phase induction motor.* In this motor the rotor is as used for a repulsion motor, but after starting the two brushes are lifted and the commutator short-circuited all round by means of a copper ring. The motor then runs as an induction motor.

SPEED VARIATION OF A.C. MOTORS

Standard types of A.C. motors do not permit of any real speed variation as their speeds are fixed by the frequency of the supply on which they operate. The synchronous motor has a definitely constant speed and the induction motor can

be assumed as constant speed as the maximum slip is not usually more than 5 per cent. A limited speed variation can be obtained by rotor resistances.

There are two methods by which a greater amount of variation can be obtained within limited fixed steps.

Pole-changing Motors. As the speed of an induction motor depends on the number of poles, two, three or even four different speeds can be obtained by arranging the stator winding so that the number of poles may be changed. On a 50-cycle supply a pole-changing motor will give synchronous speeds of, say, 500, 1,000 and 1,500 r.p.m. No intermediate speeds can be obtained by this method. These motors are sometimes used for machine tools, as, for example, drilling machines, and this method gives a very convenient speed change.

Cascade Induction Motors. Induction motors can be arranged in cascade form to give intermediate speeds. In this arrangement two motors are arranged so that the rotor of one motor is connected in series with the stator of the second. The supply is taken to the stator of the first motor only.

The speed of the common shaft will be equal to that of a motor having a number of poles equal to the sum of those of the two motors. The speed of a cascade arrangement is thus a low value usually an advantage for driving heavy machinery. For speed variation they can be arranged so that either the main motor can be used separately or in cascade. For instance, a combination of a 4-pole and 6-pole motor will give either 1,500 or 1,000 r.p.m. separately, or combined the speed will be

$$\frac{50 \times 60}{2 + 3} = 600 \text{ r.p.m.}$$

THE THREE-PHASE COMMUTATOR MOTOR

The only fully variable speed motor for use on three phase is the commutator motor, the most successful being that due to Schrage. The primary winding is situated on the rotor and is fed by means of slip-rings. The rotor also carries a secondary winding which is connected in the usual way to the commutator and through the brushes to another secondary winding on the stator.

Three pairs of brushes are required, each pair feeding one phase of the stator winding, as shown in the diagram. Speed variation is obtained by moving each pair of brushes relative to each other, this being done by a hand or automatic control through suitable worm-gear.

The speed range is roughly 3 to 1 for normal load—this ranging from 40 per cent. above to 60 per cent. below synchronism. The speed varies from 5 to 20 per cent. with the load, but this can of course be counteracted by further movement of the brushes. Motors usually start by placing brushes in lowest speed position, giving a starting torque up to $1\frac{1}{2}$ times full load torque.

These motors are expensive in first cost but have proved very satisfactory for driving machinery requiring speed control, such as printing machines, textile mills, etc.

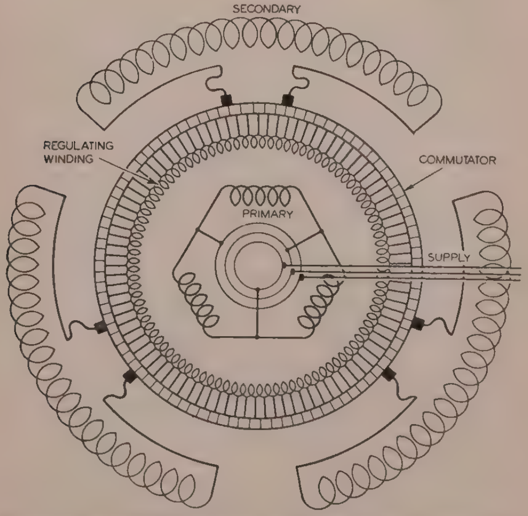


DIAGRAM SHOWING WINDINGS OF THREE-PHASE COMMUTATOR MOTOR.

CHARACTERISTICS OF VARIOUS MOTORS

Type.	Speed Variations on Load.	Possible Speed Control.	Starting Torque.	Starting Current.	Notes.
D.C. Shunt.	Reduces up to 10% from no load to full load	Can be increased up to 40% by shunt control	1½–2 Full Load	1½–2 Full Load	General purpose use. Speed usually assumed as constant. Shunt speed regulation useful in many cases
D.C. Series	Varies with load	No real control. Can be varied by series resistance	2–3 Full Load	2–3 Full Load	For traction type loads where starting torque and overload capacity is important. Must not be run with load removed
D.C. Compound	Can be arranged to vary as required up to 30% either way	As for D.C. shunt	1½–2 Full Load	1½–2 Full Load	Used for heavy duty work such as lifts. Amount of series characteristic can vary and should be stated when ordering
A.C. Polyphase Induction Squirrel Cage	Falls up to 5 or 6% from no load to full load	No variation or control possible	½–1 Full Load	1½ 2 Full Load	Standard industrial motor. Speed assumed constant for general use. Has an overload capacity of over twice full load

A.C. Polyphase Induction High Torque	As above	None	1–2 Full Load	1½–2½ Full Load	Several makers supply specially designed motors with high starting torque with moderate starting current
A.C. Polyphase Induction Slip-ring Wound-rotor	As for squirrel cage	Can be varied by rotor resistance, but variation depends on load. Up to 30% approx.	1–1½ Full Load	1½–2½ Full Load	For general use where motor must start up on heavy load. Otherwise performance similar to squirrel cage
A.C. Polyphase Commutator	Varies up to 20% for one brush position	Variation 3 to 1 by moving brushes	1½–2½ Full Load	1½ 2 Full Load	The only A.C. variable speed motor for moderate or large sizes. Expensive in first cost. Speed control is ideal
A.C. Synchronous	Constant [Power-factor can be varied.]	None	None	—	For large continuously running drives. The auto-synchronous starts as an induction motor giving F.L. torque
A.C. Single-phase Induction Split-phase	Falls slightly as load increases up to 6 %	None	1-1½ Full Load Small Powers only	2–3 Full Load	Used for small powers only on account of high starting current. Speed assumed constant

CHARACTERISTICS OF VARIOUS MOTORS—continued

Type.	Speed Variations on Load.	Possible Speed Control.	Starting Torque.	Starting Current.	Notes.
A.C. Single-phase Capacitor	As above	None	$\frac{1}{2}$–1 Full Load	1–2 Full Load	Used where it is desirable to limit starting current and give good starting torque and high power factor. Also used on account of absence of radio interference
Ditto High Torque	As above	None	$1\frac{1}{2}$–2 Full Load	2–3 Full Load	
A.C. Single-phase Repulsion Start	As above	None	2–3 Full Load	2–3 Full Load	For small motors for heavy duty
A.C. Single-phase Series (universal)	Speed varies with load, falling as load increases	Can be varied by series resistance as motors are small	1–2 Full Load	2–3 Full Load	For very light duties such as fans, etc., for domestic use

MOTOR CONTROL GEAR

Industrial control gear for motors has developed in the direction of automatic operation by means of push button and similar control. In many cases the operation of starting is by means of a lever, but in nearly all cases stopping is by means of push button. This means that all starters have some form of "latching-in" device which keeps the starter in the on or run position. This device may not take the form of a latch but may be electro-magnetic.

Contactor Control Gear.—The use of contactors for motor starters originated with heavy duty D.C. motors where it was impracticable to have manual operation of large contacts for the various steps of starting, and in addition more rapid make and break was possible by electro-magnetic operation.

The principle of a simple contactor is shown in Fig. 1, the circuit being made by energizing the operating coil. The contactor remains closed as long as the current flows in the operating coil, and if necessary a locking contact may be arranged as shown in Fig. 2 to keep the contactor closed after the control circuit has been opened by the operator releasing the starting button. With this arrangement the contactor is opened by breaking the circuit of the operating coil by pushing the stop button shown in this diagram.

The arrangement shown in Fig. 2 can be termed electrical locking, and it has the advantage that the contactor will automatically return to "off" should the supply fail.

Mechanical latching in is shown diagrammatically in Fig. 3—this including mechanical release but no "no-volt" device. Where no-volt protection is required with mechanical "latching-in" the latch is kept in position by means of a no-volt coil, and the contactor will remain closed only while the supply is live. The advantage of mechanically "latched-in" contactors is that during the running period there is no current in the operating coils, but only in the no volt coil which has a very low consumption. In addition, the operating coils can be made somewhat lighter when not left continuously in circuit.

MOTOR CONTROL GEAR

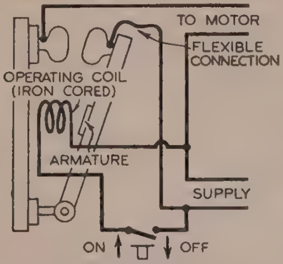


FIG. 1

SIMPLIFIED DIAGRAM OF CONTACTOR FOR MOTOR STARTER

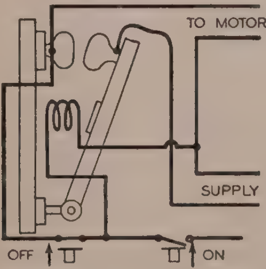


FIG. 2

CONTACTOR WITH ELECTRICAL LOCKING

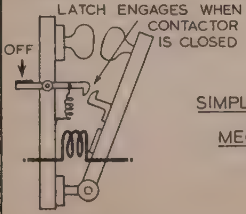


FIG. 3

SIMPLIFIED SKETCH SHOWING MECHANICAL LATCHING-IN OF CONTACTOR

Overload Protection.—The prevention of damage to a motor due to excessive current is an important function of motor control gear. Excessive current may be due to either mechanical overload on the motor or to a defect in the motor itself. In either case it is essential that the supply should be disconnected before any damage is done to the motor. An overload device thus usually operates by releasing the locking or latching-in device. Where there is a no-volt coil this is effected by disconnecting the supply to this coil, thus releasing the contactor mechanism.

Time-lag Considerations.—In connection with overload protection it is generally essential to guard against unnecessary operation due to temporary overloads due to the normal operation of the machines which are being driven. The detrimental effect of an overload on a motor is a matter of time—a slight overload taking considerable time to develop sufficient heat to do any damage, whereas a heavy overload must be removed much more quickly.

Overload devices therefore usually have a time-lag feature giving a curve of which Fig. 4 is typical. Both the overload value should be adjustable and also the time feature for important motors. For D.C. or single-phase one overload device is usually sufficient, while for three-phase at least two of the lines must be protected, and it is considered advisable by many engineers to have an overload device in each phase. A three-phase motor will often run as a single-phase machine if one line gives trouble, and this is often avoided by protecting all three lines.

Overload Devices.—These are generally of two types —electro-magnetic and thermal. The electro-magnetic type consists of a coil or solenoid carrying the line current (or a proportion of it) with an armature which when attracted sufficiently operates the release circuit or latch. A time-lag feature is obtained by means of a dash-pot or similar arrangement as otherwise the action would be practically instantaneous.

Thermal overload devices have been developed to a considerable extent due to their low cost. They may be bi-metal strips or expansion elements, and in either case, as the action is due to their heating up, a time element is always present. The expansion type has the advantage that it can be adjusted more readily and is probably more consistent in operation.

Thermal overloads are usually confined to the smaller

control units up to 20 or 30 h.p., but it will be realized that, with modern industrial tendencies, small motors represent a very large proportion of the machines now being installed.

Multi Push-button Control.—In the case of electrically operated contactor gear both starting and stopping can be controlled from any number of points by connecting additional push buttons either in series or parallel, as required. This has a definite advantage when it is inconvenient to have the control gear mounted close to the place where the operator is situated. For emergency stopping any number of "stop" buttons may be used to save time in cases of emergency.

The same principles are used in connection with interlocking for lifts and similar machinery where it is necessary for certain items to be in position before the machine can be started up.

Multi-stage Starters.—Direct-on starting is allowed for motors up to a certain size—the limit being fixed by the supply authority, but varying from 1 to 5 h.p. Above this it is necessary to employ some method of starting which limits the starting current to between two and three times full-load current. For squirrel-cage motors this means either star-delta or transformer starting, and in either case this is effected in contactor starters by employing two contactors with either a series or time relay for the change-over.

For wound-rotor motors hand-controlled starters are in more general use, but contactors can be used—one main contactor for the stator and two to five stages for cutting out the rotor resistance.

The change-over from one stage to another may be controlled by current or time. For current control a current or series relay is used to operate the change-over from one contactor to the next when the current has fallen to a certain value by virtue of the motor speeding up. This method ensures more correct starting but requires fairly accurate adjustment.

The time relay control is by means of a dash-pot time-lag or similar device, and as soon as the first contactor is operated the relay comes into circuit. After the set time has expired the change-over takes place and the process is repeated for subsequent stages.

Wound-rotor Starters.—Where slip-ring motors have to start up against severe load conditions liquid resistance starters are found very satisfactory. By varying the electrolyte the added resistance is under control, and liquid starters have the advantage ; the resistance is reduced continuously and smoothly instead of by steps as in other systems.

Air-break Limits.—Air-break switchgear and starters are only satisfactory up to a certain size. For D.C., however, air-break gear is used up to several hundred horse-power, but it is necessary to renew the contacts fairly frequently.

For controlling A.C. motors air-break gear is satisfactory up to about 30 h.p., but for larger outputs oil-break gear is generally specified. Both contactors, hand-operated switches and rheostats may be oil immersed and oil-break gear is on the market for very low currents of a few amperes.

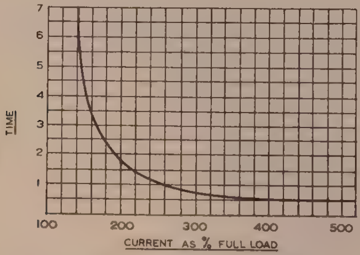


Fig. 4.—Curve showing Variation in Speed of Operation with Load for Overload Time Lag.

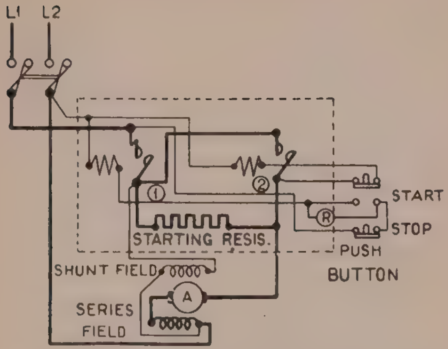
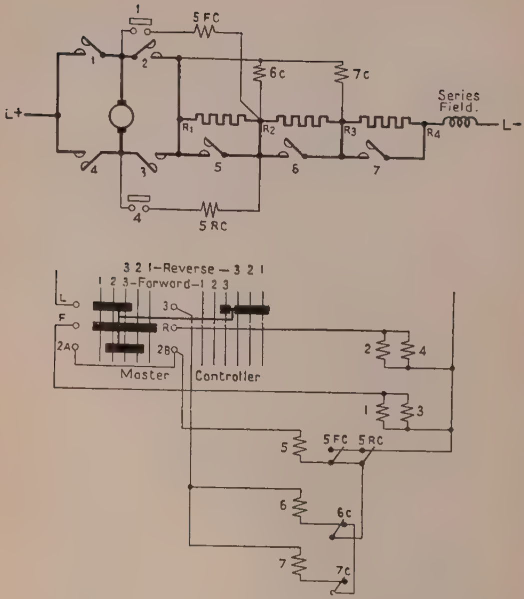


Fig. 5.—Typical D.C. Contactor Starter.

Contactor No. 1 is the line contactor.
Contactor No. 2 is the running contactor.

Above diagram shows D.C. starter with two-stage operation and controlled by push buttons. Diagram shows connections for a compound-wound motor, but starter can be used for shunt, series or compound. The pressing of the start button closes contactor No. 1, starting the motor with the resistance in circuit. The operating coil of the second contactor is connected across the motor armature and operates as soon as the motor voltage reaches a certain value. The main contactor acts as a no-volt device and overload protection can be added.



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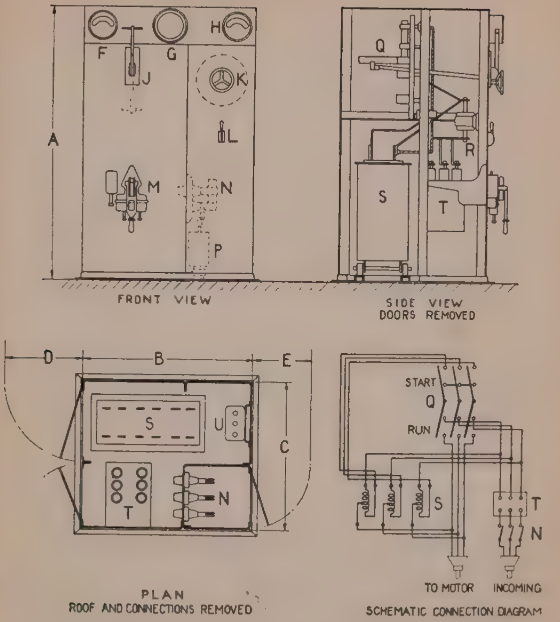
Relay 5 RC	controls	Contactor	5 in reverse direction
,, 5 FC	,,	,,	5 in forward ,,
,, 6 C	,,	,,	6 in either ,,
,, 7 C	,,	,,	7 in either ,,

Fig. 6.—Typical D.C. Contactor Equipment for Reversing Heavy Duty Motor.



(*B. T.-H. Co. Ltd.*)

F = Ammeter (stator).
G = Power factor meter.
H = Ammeter (field).
J = Operating handle of air-break change-over switch.
K = Operating handwheel for exciter field rheostat.
L = Field switch.
M = Operating handle for oil-circuit breaker, with over-current trips and under-voltage release.
N = Isolators (if required).
P = Cable-box.
Q = Air-break change-over switch.
R = Current transformers.
S = Auto-transformer.
T = Oil circuit-breaker.
U = Cable rack.

Typical Auto-transformer Starting Panel.


CIRCUIT BREAKERS
OIL
STATTER
AIR
J. G. STATTER & CO., LTD., 82, VICTORIA ST., S.W.1.

SWITCHGEAR

The choice of suitable switchgear depends to a larger extent on the actual duty than any other type of electrical plant. In addition to switching on or off any section of an electrical installation, the switchgear generally includes the necessary protective devices which are desirable in order that the particular section may be automatically isolated if conditions become unsatisfactory.

Originally all switchgear consisted of open knife switches mounted on a slate or composition panel and operated by hand. The protective device consisted of a fuse which was generally mounted close to the switch. The use of high voltage A.C. and the great increase in total power in a system necessitated the use of oil-break switchgear.

For low voltages (up to 600 volts) knife-type switches are still used, and in some instances open-type boards are being installed, but generally most switchgear is to-day enclosed. Ironclad switch or combined switch and fuse units are used either singly or grouped to form a switchboard. For the smaller capacities insulated cases are obtainable in place of the iron type, these being particularly popular for domestic installations.

The knife switches are usually spring controlled, giving a quick make and break with a *free handle* action which makes the operation of the switch independent of the speed at which the handle is moved. In all cases it is impossible to open the case with the switch in the "on" position, and this safety device must not be removed. The normal limit for this type of switch is from 300 to 400 amps., but larger units can be made specially.

For arduous and frequent use, oil-break gear is preferred even for voltages of 400 three-phase, and they are essential for high-voltage A.C. gear of all kinds. The value of breaking the contact under oil is that the oil prevents the arc from reforming after it has been broken during the instant the current wave passes through zero. They are not normally used on D.C. as the quenching of the D.C. arc (which is probably augmented by inductive action) causes the oil to carbonize quickly. With A.C. the amount of arcing is very small.

The control of large-capacity oil-break switchgear is generally operated by a solenoid or by a motor. With the use of a solenoid it is sometimes necessary to provide a supply of

D.C., whereas with motor control low-voltage three-phase A.C. can be employed. In most switchgear the action is by means of a toggle arrangement controlled by a strong spring which ensures quick operation.

For ordinary distribution voltages three-phase units are used, but for the extra high pressures used on the Grid Scheme three separate single-phase breakers are installed. Protection from overload is obtained by means of a releasing device which releases the control spring and opens the switch. For small switches the protection is obtained by means of overload coils or thermal releases inside the switch itself. For large units which are protected by some special system of protective gear the operation of one of the relays of the protective system releases the spring in a similar manner.

Some essential features of oil-break switchgear are:

(*a*) Isolation of internal mechanism for inspection. This is important and full interlocks are always provided to prevent opening of any part of the enclosure unless every part of the switch mechanism is disconnected from the supply.

(*b*) Quantity of oil and clearance from switch contact to sides of tank must be adequate for voltage and maximum load which the breaker will be called upon to deal with.

(*c*) Provision for manual operation in case the electrical control (if provided) fails to operate.

(*d*) Provision for any instruments which may be required. These may be in the form of either ammeter or voltmeter on the switch itself or the necessary current and potential transformers for connecting to the main switchboard.

For high tension work oil-break switchgear is isolated in the following ways:

(*a*) By isolating links in or near the busbar chamber.

(*b*) Draw-out type of gear in which the whole of the switch mechanism is withdrawn from the busbar chamber before it can be opened up.

(*c*) Truck-type, which is pulled away completely before inspection or adjustment.

It should be noted that in certain cases, double isolating devices are necessary, i.e. both on the incoming and outgoing side. Isolation is, of course, always required on the incoming side, but it is also necessary on the outgoing side if that part of the network can be made alive through any other control gear or alternative supply.

It is interesting to note that one explanation of the difference between the switch and the circuit breaker is that whereas the switch is a device for making and breaking a

current not greatly in excess of its rated normal current, the circuit breaker is a device capable of making and breaking the circuit under both normal and abnormal conditions.

On this account high-voltage heavy-duty gear often has a working rating and a maximum rating.

There is to-day a large amount of research work still being carried on both in the laboratory and by interchange of views between manufacturers all over the world.

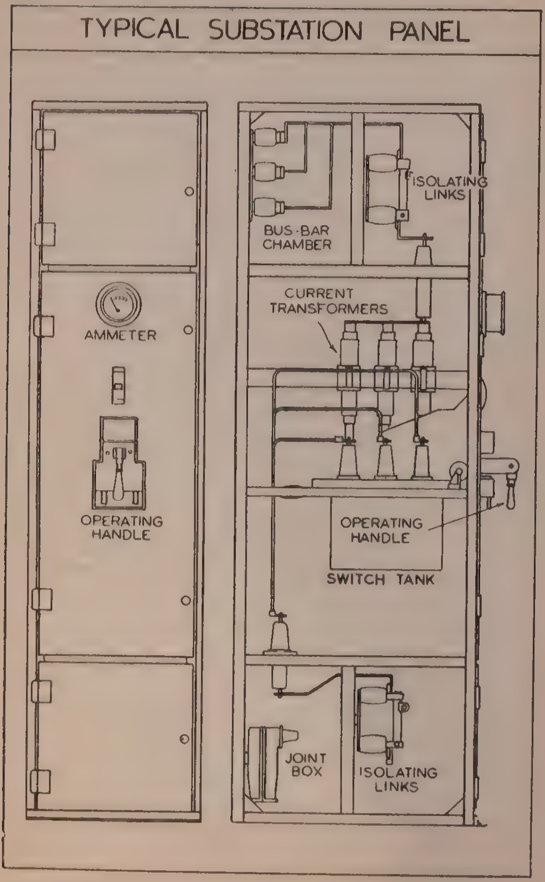
The International Electrotechnical Commission (I.E.C.) aim at setting up an international specification for A.C. circuit breakers.

A breaker is usually classified according to the voltage of the circuit on which it is to be installed; the normal current which it is designed to carry continuously in order to limit the temperature rise to a safe value; the frequency of the current; its interrupting capacity in kVA; its making capacity in amperes, i.e. the instantaneous peak current; and the greatest r.m.s. current which it will carry without damage for a specified length of time, usually five seconds.

A number of oil circuit-breaker kVA rupturing capacities have been standardized for use in this country. These capacities are given in the table which is reproduced from the British Standard Specification, No. 116.

STANDARD CURRENT-BREAKING CAPACITY RATINGS FOR THREE-PHASE CIRCUIT BREAKERS

Standard Breaking Capacity Rating. kVA.	Standard Voltage Ratings.					
	660.	3,300.	6,600.	11,000.	22,000.	33,000.
5,000	4,400	880	—	—	—	—
10,000	8,800	1,760	880	—	—	—
15,000	13,000	2,600	1,300	—	—	—
25,000	22,000	4,400	2,200	1,300	—	—
50,000	44,000	8,800	4,400	2,600	1,300	—
75,000	66,000	13,000	6,600	3,900	2,000	1,300
100,000	88,000	17,600	8,800	5,200	2,600	1,750
150,000	—	26,000	13,000	7,800	4,000	2,600
250,000	—	44,000	22,000	13,000	6,600	4,400
350,000	—	61,000	30,500	18,500	9,250	6,100
500,000	—	88,000	44,000	26,000	13,000	8,800
750,000	—	—	66,000	40,000	20,000	13,000
1,000,000	—	—	88,000	52,000	26,000	17,500
1,500,000	—	—	132,000	80,000	40,000	26,000


TYPICAL SUBSTATION PANEL
AMMETER
OPERATING HANDLE
BUS-BAR CHAMBER
ISOLATING LINKS
CURRENT TRANSFORMERS
OPERATING HANDLE
SWITCH TANK
JOINT BOX
ISOLATING LINKS

OVERLOAD AND FAULT PROTECTION

The protection of both plant and transmission lines has reached a very high state of perfection and faulty sections can now be automatically isolated before a fault or overload can cause any damage to the section itself or the remainder of the system of which it is a part.

In all the different methods the essential feature is that of isolating the faulty section, and in considering the principles of the various systems of protection it is usually understood that the actual isolation is carried out by means of circuit breakers which are operated by means of currents due to the action of the protective gear. Usually the required operating current for the breaker is controlled by relays which are in turn operated by the protective gear.

Similar principles are used for the protection of machines such as alternators, transformers, etc., as for overhead lines and cables. The essential difference is only a matter of adaptation, the most important difference being the fact that on transmission lines and feeders certain systems require pilot wires connecting the protective apparatus at each end of the line and these are sometimes undesirable. With machines this point is unimportant as the two sets of gear—one on each side—are not separated by any real distance.

With all systems one or both of the following two undesirable features are guarded against—namely, *overload* and *faulty insulation*. The overload conditions which make it necessary to disconnect the supply may be due to faulty apparatus or to an overload caused by connecting apparatus of too great a capacity for the line or machine. The faulty insulation or *fault* conditions may be either between the conductors or from one or all the conductors to earth.

In connection with all protective gear the following terms are generally used :

Stability Ratio.—This may be termed the measure of the discriminating power of the system. The stability is referred to as the maximum current which can flow without affecting the proper functioning of the protective gear. Stability ratio can also be defined as the ratio between stability and the sensitivity.

Sensitivity is variation in current which will operate the protective gear. In the case of feeders and transmission lines this is normally the difference between the current entering the line and the current leaving it.

OVERCURRENT RELAYS

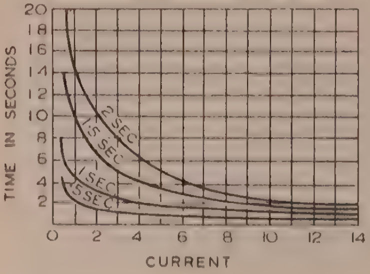


FIG. 1 INVERSE TIME-LAG CHARACTERISTICS OF OVERCURRENT RELAYS

FIG 2 GRADING OF OVERCURRENT RELAYS

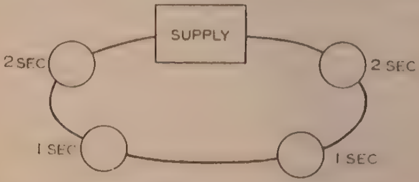


FIG 3 GRADING FOR RING MAINS

OVERLOAD RELAYS

The simplest form of protection is that of the early circuit breaker which is released as soon as the current exceeds a predetermined value. For D.C. circuits of small capacity simple overload breakers are usually mounted on the switchboard over the rest of the switchgear. For high-tension A.C. the main circuit breakers must be used and the trip coils of these breakers are operated by overcurrent relays with graded time-lag characteristics.

The time characteristics will be seen from the curves in Fig. 1, which show how the time-lag between the overload occurring and the gear operating is inversely proportional to the amount of the overload. The setting or time lag usually used to indicate how the relay has been adjusted is that of short-circuit conditions so that the settings of the four relays for which the curves are drawn would be as marked.

The principle of grading on a system is that of decreasing the setting as we proceed away from the source of supply. The use of the four relays for which the curves have been drawn would be used as shown in the diagrams in Figs. 2 and 3. Fig. 2 represents a distributor fed at one end, whereas Fig. 3 shows a ring main. A distributor fed at both ends is similar to Fig. 3.

Modern overcurrent relays are usually of the induction type. The action is similar to that of an induction wattmeter. A metal disc rotates against a spring, the angle of rotation being proportional to the current. As soon as the disc has rotated through a certain angle the trip circuit is closed. As the speed of rotation is proportional to the load the inverse time element is obtained and the time-setting is adjustable by altering the angle through which the disc has to turn before making the trip circuit.

DIRECTIONAL PROTECTION

In addition to overload protection it is often desirable for immediate interruption of supply in the case of a reverse current. In this case directional relays are used and these can be combined with overcurrent relays when required as shown in Fig. 4. The use of directional and non-directional relays is shown in the system reproduced in Fig. 5.

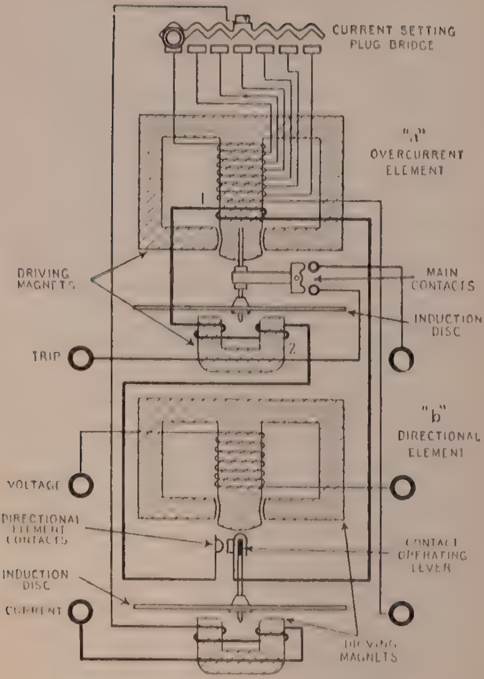


FIG. 4.—Directional Overcurrent Relay.

IMPEDANCE RELAY PROTECTION

Owing to the extension and complication of transmission and distribution systems, it becomes difficult to obtain sufficient discriminination in certain cases with overcurrent and directional relays with time limit features. For these cases impedance relays have proved satisfactory.

The principle of the impedance relays is that the relation between the fault current and the voltage at the point where the relay is connected will depend on the impedance of the feeder or line between that point and the fault, the value being given by

$$Z = \frac{E}{I}.$$

Thus a relay having a current element, the torque of which is opposed by the torque of the voltage element, can be arranged so that the trip circuit will close if the ratio E/I becomes less than the impedance of the section it is protecting.

Impedance relays are of several types, a definite impedance relay of the induction type being shown in Fig. 6. Another form is the impedance-time relay which is used where it is desirable to operate after a definite time-lag when the fault is at the remote end, but with decreasing time as the position of the fault is nearer to the relay.

With impedance relays it is often necessary to compensate for the resistance of an arc which may be formed under fault conditions. This may be done in several ways, one of which is to connect an adjustable resistance in series with the current coil of the relay.

PILOT WIRE SYSTEMS

Protective systems requiring pilot wires for use on transmission lines operate on the principle of unequal currents and are referred to as differential systems. The same methods are used for machine protection, the pilot wires being, of course, much shorter and thus not referred to as pilot wires in this case.

The essential principle is that if the current entering a conductor is the same as that leaving it there is no fault, but as soon as there is a difference more than is considered advisable the supply is disconnected.

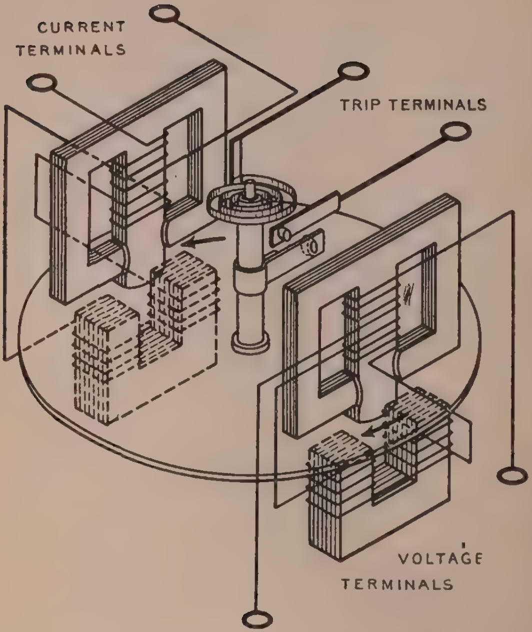


Fig. 6.—Induction-type Definite Impedance Relay.

PROTECTIVE SYSTEMS

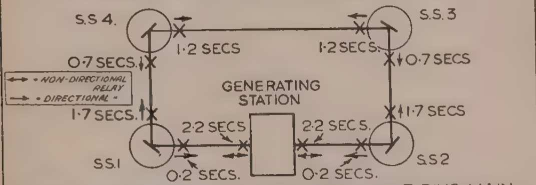


FIG 5 DISCRIMINATIVE TIME PROTECTION OF RING MAIN

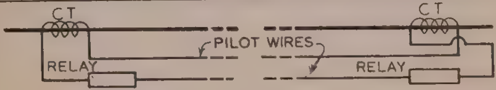


FIG.7. BALANCED VOLTAGE. SYSTEM

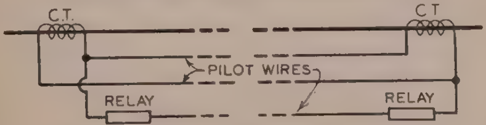


FIG 8 BALANCED CURRENT SYSTEM

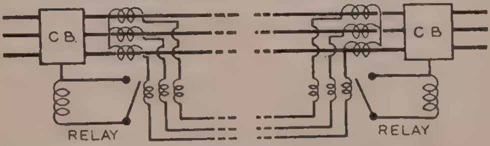


FIG 9 THREE-PHASE MERZ-PRICE SYSTEM

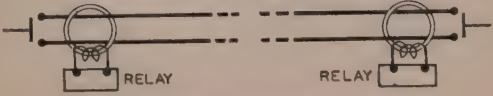


FIG11 THE SPLIT CONDUCTOR SYSTEM

Both *balanced voltage* and *balanced current* systems are in use. Current transformers are situated at each end of the conductor and either the voltage or current in the secondaries are balanced one against the other. For balanced voltage these are placed *back-to-back* and no current flows for correct conditions. For balanced current, the secondaries are placed in series and current flows in the pilot wires. In this case fault conditions are remedied by a cross-connection as shown in Fig. 8. In general, balanced voltage is used for protecting transmission lines and balanced current for protecting machines.

The balanced voltage system was developed for line protection by Messrs. Merz and Price and is known as the Merz-Price System. There have been several modifications and most manufacturers have their own particular method of applying this principle and improving the actual performance compared with the original simple Merz-Price System.

All these systems cannot be dealt with in detail, but one or two will be described. A simple 3-phase arrangement is shown in Fig. 9. It will be seen that three pilot wires are required in this case.

The disadvantages of the simple Merz-Price System include instability, insensitive setting required to prevent operation on no-fault conditions and the high voltages in the pilot wires.

A typical modification is the Translay System in which induction type relays are used instead of the usual electromagnetic type. The circuit (simplified) is given in Fig. 10.

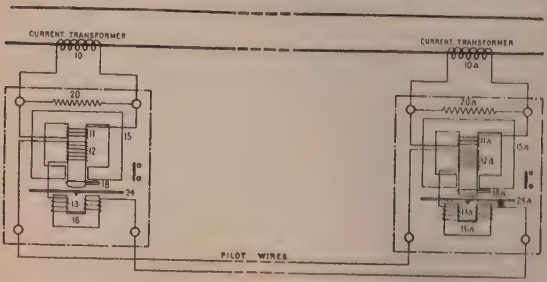


FIG. 10.—The Translay System for Single-phase Feeder.

The relay primary winding is energized from the secondary of a current transformer and in addition to setting up a leakage flux which, in conjunction with a suitable flux from the lower magnet, causes the non-magnetic disc to rotate, it acts also as the primary of an air-gap transformer causing a voltage to be generated in the secondary winding. The value of this secondary voltage depends on the current flowing in the primary winding, and as the secondary windings of the relays at opposite ends of the feeder are connected in opposition through the pilot wires, no current will flow in the circuit under normal conditions. In the case of a fault, there is a discrepancy between the currents flowing at the two ends, and the resultant difference between the secondary voltages will cause a current to flow in this circuit. The flux set up by this current will, by interaction with the leakage flux, cause the relays to operate.

This system, which has been developed by Messrs. Metropolitan-Vickers Electrical Co., removes many of the disadvantages mentioned.

SPLIT-CONDUCTOR SYSTEM

This is used for underground cables and consists of splitting each conductor into two sections, as shown in Fig. 11. The two sections are taken through a current transformer in opposite directions so that normally there is no current in the secondary winding. Should a fault occur it will affect the two sections differently and thus upset the balance, thus operating the relays.

One important point in connection with this system is that the "split" must be taken right into the breakers, which must thus be duplicate for each conductor. Special breakers are available for this purpose.

McCOLL BIASSED SYSTEM OF PROTECTION

The McColl System of Protection uses a biassed system with a view to obtaining protective operation on faults of 5 per cent. to 10 per cent. of the normal load. With the simpler forms of valanced protection it is sometimes necessary for the fault to be between 100 per cent. and 200 per cent. of the normal load for the protective gear to operate. This is due to the insensitiveness which is necessary at high over-

Mc COLL BIASSED PROTECTION

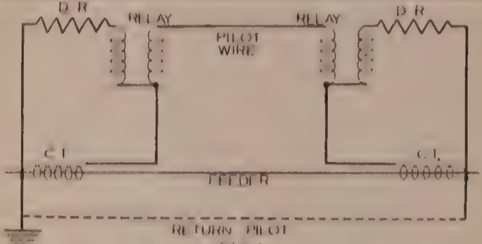
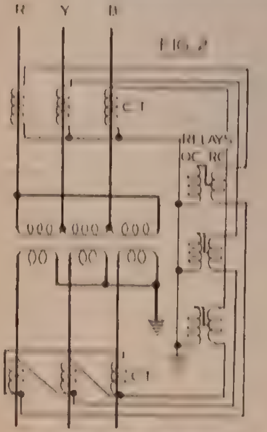


FIG. 1

PRINCIPLE OF Mc COLL BIASSED SYSTEM FOR PROTECTION OF FEEDERS

FIG. 2



TRANSFORMER PROTECTION (STAR DELTA CONNECTION)

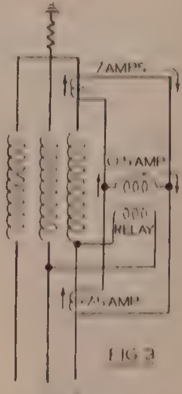


FIG. 3

ALTERNATOR PROTECTION

loads in order to obtain stability. Too close a setting may result in a state of unbalance due to ratio errors in current transformers under overload conditions.

With a biassed system it is possible to vary automatically the sensitiveness of the protective gear in accordance with the load. Most biassed systems are inherently selective and only the faulty section is shut down, thus putting out of action the minimum amount of equipment. Another important feature is its instantaneous operation.

General Principles.—The general system will be seen by reference to Fig. 1, which shows the McColl System applied to a feeder. Current transformers are located at each end and pilot wires connect the secondaries of these transformers to the relays which operate the control gear. A secondary current proportionate to the load flows through both current transformers and along the pilot wire, passing through the restraining windings (R.C.) of the relays. Any excess current in either transformer due to a leak in the feeder passes only through the local circuit, which includes the operating coil (O.C.). Should this latter current be sufficiently large in comparison with the current flowing through the pilot wires and the restraining coils the relay will operate, thus isolating the feeder.

The local circuit at each end is formed by means of duplicate resistances (D.R.) which are such that the secondary currents divide equally between the pilot wire and the local circuits when everything is in order. Immediately a fault occurs this equality is upset, and when it is large enough in comparison with the load the relays operate the switchgear.

The bias feature is obtained by means of adjusting the position of the fulcrum for the armature of the relay, this being arranged so that its normal position is in the direction of the restraining coil, thereby keeping the feeder alive. Similar arrangements are used for protecting generators and transformers and this system can also be applied for the protection of parallel feeders. Simplified diagrams for some of these circuits are given here, one of these being amplified by means of current values, showing the state of affairs which occurs under fault conditions.

SMALL GENERATING PLANTS

The extension of the public supply during the last decade has tended to retard the installation of private generating plants except at two rather opposite ends of the scale. These are the small private plant for use in country districts where the public supply is not available or is not economical, and the large power-stations installed at factories where the load is so great that a self-contained plant is desirable.

The small generating plant received a new lease of life with the introduction and perfection of the Diesel engine. Working on crude oil, it has an economic efficiency that enables it to compete with the public supply, and it is now the standard method of generating electricity except in the case of very small or very large plants.

The smallest Diesel set made commercially gives about 1 kilowatt, but up to 3 or 4 kilowatts the petrol engine is a competitor. Over this and up to units of 1,000 kilowatts the Diesel engine is used. For very large plants of several thousand kilowatts the modern steam plant is still the most economical.

Small generating plants of from 300 watts to 50 kilowatts have now reached a very advanced stage of development and now include a fair amount of automatic control.

Non-automatic Plants.—These are usually battery plants run for a few hours each day to charge the battery which supplies the load at all times. Both Diesel and petrol engines are used and starting may be by hand or from the battery. The size of plant must be fixed so that the battery will supply the maximum load likely to be required over a period of at least 48 hours so that charging is not required every day. The engine size will be controlled to some extent by the battery, as charging must be at the 8- or 10-hour rate.

A typical country house plant is as follows:

Normal full load output of battery—20 *lamps, say* 750 *watts.*
Estimated maximum watt-hours in 48 *hours*—10,000.
Total battery capacity—10-*hour rate*—13,750 *watt-hours.*
Details of battery—60 *cells of* 125 *ampere-hours capacity.*
Maximum charging rate—8-*hour rate*—16 *amps.*
Output of generator—18 *amps. at* 110 *to* 170 *volts.*
Kilowatt rating—3,060 *watts*—3 *kilowatts approx.*
Engine required—*double kilowatt output*—6 *h.p.*

In actual practice it would be found that under ordinary circumstances the above plant would run satisfactorily if the battery is charged up two or three times per week, and in the summer the engine would be available for a whole week for inspection and overhaul if necessary.

Fully Automatic Plants.—As an alternative to the battery plant, fully automatic plants can be obtained which supply the load direct from the generator. These plants always start up automatically and a small starting battery is used for this purpose. A typical example of this is the Kohler system, which uses a large car type battery for starting up the plant.

As soon as a switch is closed this starting battery automatically closes contactors which connect it to a special winding on the generator, thus starting the engine. The plant continues to run until all load is switched off, when it shuts down. The starting battery is charged up while the engine is running. This system is used for plants from a few hundred watts to units giving 20 or 30 kilowatts.

Floating Battery Sets.—A modification of the fully automatic set as described above is that where a small capacity battery is used with automatic operation. In this case a battery (of full line voltage) is used to carry small loads of one to ten lamps. The control gear is arranged so that as soon as the load exceeds a certain value (from $\frac{1}{10}$ to $\frac{1}{4}$ of normal full load) the engine is automatically started by the floating battery and the whole of the load is then supplied by the engine until it reaches the maximum output of the set. In some cases, should the load be more than this, the balance is then supplied by the battery.

These sets are fully automatic and do not need any regular attention except for seeing to the supply of fuel and oil and the usual attention to both engine and battery. The automatic control ensures that the battery is always kept in a charged condition.

Apart from the floating battery system as outlined above, plants with a full-size battery are also now entirely automatic, and these are arranged for the load to be taken from the battery only or from both the battery and the engine as required.

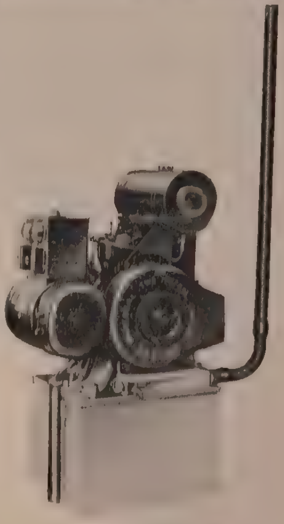
Voltage and Supply.—As it is desirable to keep the number of cells fairly low, plants using a main or floating

battery are usually either 50 or 110 volts, and of course D.C. has to be used. Above 5 kilowatts, 220 or 240 volts can be used and where economical this voltage is an advantage from the point of view of any change-over to public supply at a future date.

With fully automatic plants using only a starting battery any voltage can be used, and in this case A.C. can be generated. (A rectifier is used to charge the starting battery.) For the very small sets D.C. is still more practicable, but A.C. sets have been developed very successfully for emergency use in case of failure of the public supply.

Composite Plants and Stand-by.—Where the main load is supplied by the engine it is desirable to have a stand-by plant, and there is also the question of widely varying load. Both these points are met by installing two plants of either the same or different outputs. For example, if the load occasionally amounts to 10 kilowatts, either two 6-kilowatt plants or one 4- and one 7-kilowatt plant could be put down.

In either case one engine starts up first and the second comes into operation as soon as the load is larger than can be handled by one engine. With the small and large plant a further arrangement is that the small plant runs for low loads, and if it increases further the load is transferred to the large plant, the small plant coming in again later if required. With either scheme a limited supply is available should one engine fail or be under repair.



Petter Generating Set.

GENERATING COSTS FOR PRIVATE PLANTS

THERE are generally many misunderstandings in connection with the cost of generating electricity by means of a private generating plant. These are due to the difference between actual running costs for fuel and oil only and the total production costs which include interest and depreciation on capital cost, rental cost of engine-house, wages and payments for upkeep and repairs, insurance and certain incidental overhead costs.

Small plants of a few hundred kilowatts cannot generate at as low a cost as a modern super-station, but in the case of the private plant there are no distribution costs, which in the case of public supply are more than the actual cost of generation.

As a guide to the method of determining probable costs for a private plant the following may be taken. This is for a 200-kW Diesel plant, and for plants from 100 to 1,000 kW the cost will be roughly proportional. For smaller plants the cost will be higher per unit, but even for a 10-kW the increase will not be excessive unless an attendant is employed specially for a small engine of this size.

Costs for 200-kilowatt Diesel Plant.—The plant and equipment would cost (including installation) about £4,000 and the engine would have a fuel consumption of 0·55 lb. per kW.

Assuming normal running of 50 hours per week for 52 weeks per year, typical costs would be as follows:

		£	
Overhead Costs			
Interest and Depreciation—	10%	400	
Insurance—	2%	80	
Maintenance—	1%	40	
Attendance, cleaning, etc.		200	
			720
Running Costs			
Fuel—112 tons at £6		672	
Lubricating oil—5% of fuel cost		34	
			706
Total annual cost			£1,426

The oil and fuel consumption has been based on a load factor of about 90 per cent. (in many cases it would be less) and the number of units generated in the year would be $180 \times 50 \times 52$ = say 460,000 units. On this basis the cost per unit works out at

$$\frac{1,426 \times 240}{460,000} = 0{\cdot}75d. \text{ approx.}$$

It will be seen that the above is a fairly ideal case for low generating costs, but it can be assumed that electrical energy can be generated at a cost of between $\frac{1}{2}d.$ and $1d.$ per unit. The cost is increased if standby plant is essential to guard against possible interruption of supply, but is reduced for continuous running for longer periods per day or week.

ELECTRICITY TARIFFS AND COSTS

TARIFFS for the supply of electrical energy have in the past been based on the price which the consumer would be willing to pay as well as on the actual cost of supplying the energy. On this account different charges were made per unit for such services as lighting, heating and power.

As, however, electricity is not a commodity which can be stored and used as required the flat-rate basis was found unsatisfactory and two-part tariffs in some form or another are rapidly replacing fixed rate tariffs of so much per unit.

The Cost of Supplying Energy.—The cost of electrical energy is made up of two main divisions, viz. :

1. The capital cost of providing the necessary generating plant and distributing equipment plus overhead costs not dependent on the amount of energy used.
2. The actual cost of generating each unit and transmitting it to the consumer.

The important point is that the first cost is independent of the amount of energy used and is proportionate to the maximum demand of the consumer. As explained later, allowance is sometimes made for consumers who take their energy at times of low load (i.e. off-peak consumers).

The two-part tariff is based on the two costs outlined above and the first item is covered by an annual amount and the second part by a charge per unit used.

Load Factor.—This can be defined as the average load compared with the maximum load for any given period. It can be calculated as follows:

$$\frac{\text{Actual energy consumed}}{\text{Maximum demand} \times \text{Time in hours of period}}.$$

The load factor of a consumer may vary from as low as 5 per cent. to as high as 80 per cent., but usually it ranges from 10 per cent. (for lighting only) to 40 per cent. (for industrial or heating loads). Some industries are able to offer a 24-hour load and it is in these cases that very high load factor figures are obtained.

Owing to the two-part nature of the cost of supplying electrical energy, the actual load factor has a direct effect on the cost per unit since the fixed or standing charge to cover the first cost is divided into all the units used during that period. The more units used (and the higher the load factor), the less will be the fixed cost per unit. On this account it is the aim of every supply engineer to make his load factor as high as possible. As will be explained, special inducements are generally offered to consumers who will enable him to do this.

Diversity.—Owing to the different times at which a number of consumers will take their supply the load factor of the generating or distributing system will be different from that of its consumers even if they all had the same value. If 10 consumers are connected to a section they will not all take their maximum load at the same time (except in very unusual circumstances) and therefore the maximum load of the section will be much less than the sum of the maximum loads of the consumers.

This fact, which is termed *diversity*, is very important to the supply engineer, as the higher the diversity the higher will be the system load factor compared with the average of the consumers.

The amount of diversity is given by the *diversity factor*, which is found from

$$\frac{\text{Sum of consumers' maximum demands}}{\text{Maximum demand on system}},$$

and it will be seen that

$$\frac{\text{System load factor}}{\text{Average consumer's load factor}} = \text{Diversity factor.}$$

Note.—The average consumer's load factor must be calculated with reference to actual consumptions and not merely as a numerical average.

Two-part Tariffs.—These are usually of two different types, *industrial* and *domestic.*

An industrial two-part tariff is always based on the maximum demand—either in kW or in kVA. A typical industrial tariff will therefore be

£5 per annum per kW of maximum demand plus ½*d.* per unit consumed.

It is more usual to-day to base the fixed charge on kVA so that the supply authority is compensated for any consumer taking his supply at a low power factor. Another method is to allow for power factor by means of an additional clause, varying the cost per unit by an amount proportional to the power factor *above or below* a datum of, say, 0·8. In this way the consumer is recompensed if he has a high power factor.

The maximum demand figure is obtained by means of a maximum demand indicator which gives the highest load (either in kW or kVA according to the tariff) which occurs for a given period—such as 15 or 30 minutes. Heavy loads of short duration such as those due to starting large motors are not taken into account.

For industrial consumers accounts are usually made up either quarterly or monthly and the maximum demand taken for this period. The larger the load the shorter the period, and in some cases the accounting is done every week.

Special tariffs are in many cases offered to consumers with favourable loads. Examples of this are for shop-window lighting after ordinary hours, night loads of every description, and for 24-hour loads (such as electric processes running continuously) additional concessions are often made over and above the low figures automatically obtained by the two-part tariff. In some cases with 24-hour loads the total price per unit falls to ¼*d.* per unit.

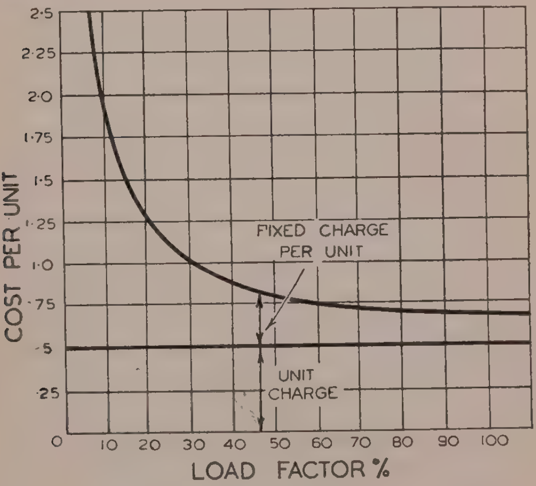
Bulk supply tariffs to large consumers also include a clause varying the consumption figure per unit according to the price of coal above or below a certain price per ton.

Industrial two-part tariffs are based to a large extent on the actual cost of the service although there is usually a tendency to keep the fixed charge as low as possible.

It has not yet been found practicable to base domestic

tariffs on the maximum demand, partly on account of its complication and unsuitability, but also on account of it not being understood by the consumer.

Fixed simple flat rate charges are still in use for small consumers, such as 4*d*. per unit for lighting and 1*d*. for heating, and for very small consumers this system has the advantage of simplicity. It results, however, in an apparent overcharge and does not encourage the consumer to use more energy.



Graph showing how total cost per unit varies with load factor. The rapid reduction from 10 per cent. to 20 per cent. should be noted. Also that over 70 per cent. the cost does not vary to any great extent.

On this account two-part tariffs are in general use based on the size of the house in some manner. The basis of the fixed charge varies but in the main two systems are in general use, viz.:

(*a*) A charge of so much per quarter per room plus a charge per unit used.

(*b*) A charge of so much per quarter based on the rateable value of the premises plus a charge per unit.

The second method is rapidly becoming the most popular —to a large extent due to its simplicity—and the fixed charge is usually somewhere about 12½ per cent of the rateable value. The unit charge varies from ½*d*. to 1*d*. and on this basis the total cost per unit for the average house is not much more than 1*d*. per unit, providing that electricity is used to a reasonable extent for purposes other than lighting.

In the first method the fixed charge may be in the region of £1 per annum per room and this charge is only made in respect of rooms which are actually used—kitchens, bathrooms, etc., not being included.

Variation in Total Cost per Unit with Load Factor.— The way in which the actual cost of the supply per unit varies with the load factor will be seen from the graph which shows the two costs for a typical two-part tariff. It will be seen that for a 30 per cent. load factor the total cost is 1*d*. per unit, whereas for below 10 per cent. (which would be the value for lighting only) it rises above 2*d*. per unit.

In fixing domestic two-part tariffs much attention has been paid to the reaction of the consumer. If worked out accurately according to costs it would be found that a higher fixed charge and a lower unit rate would in most cases be more correct. A high fixed charge acts as a deterrent and it has been found more satisfactory to keep this as low as possible. In general, a compromise has been found which appears to be fairly agreeable and successful as regards both parties. As the consumer is becoming more educated as regards the working of the two-part tariff, it will probably be the only basis of supply in the future.

The development of special prepayment meters to cover two-part tariffs has been an important factor, and now meters are available which cover the fixed charge automatically and will also make allowance for hire charges together with other payments such as assisted wiring schemes.

MEASUREMENT OF EARTH RESISTANCE

An earth resistance is not a simple resistance in the same sense as a coil of wire. The resistance is electrolytic in character and thus there is a back E.M.F. present, which, unless a special method of measurement is employed, is likely to introduce errors. Again, stray currents are very often present in the soil, these currents being return currents from electrical railway systems or leakage currents from distribution systems. These tend to upset some of the methods of measurement.

No matter what method is employed, it is always necessary to have available, or to make, one or more additional contacts with the earth, and one of the difficulties in the measurement of the resistance of an earth connection in the past has been to eliminate the resistances of these temporary connections.

Fall of Potential Method.—A method often used in the past is shown in Fig. 1. This is known as the fall of potential method. Two temporary earth connections P and C are driven into the ground at suitable distances from the earth connection under test. A known current is passed via the earth plate through the earth and returned through the "current" temporary earth connection C. The potential difference between the earth plate and the "potential" temporary earth connection P is then measured. The quotient of this potential difference and the total current flowing gives the resistance of the earth connection under test. In this method the resistance of the temporary earth connection P only affects the result indirectly. It increases the total resistance of the voltmeter circuit, but provided this voltmeter is of high resistance the effect on the final result is negligible. *It is thus possible to measure an earth resistance of low value with high resistance temporary earth connections; alternating current must be used as with direct current errors may be introduced by the back E.M.F. due to electrolysis.* When using a voltmeter and ammeter, however, the readings obtained are still subject to interference from stray currents flowing in the earth.

EARTH RESISTANCE TESTING

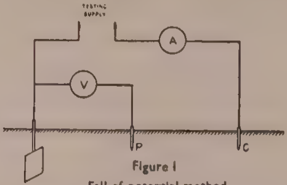


Figure 1

Fall of potential method

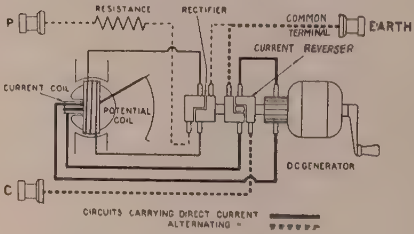


Figure 2

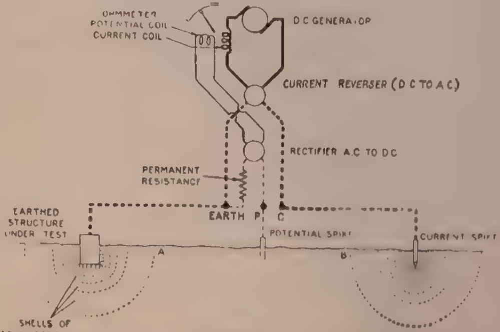


Figure 3

An interesting instrument in which the readings are unaffected by stray currents or back E.M.F. is the "Megger" Earth Tester which is a combined ohmmeter and generator of a special type, so designed that alternating current is passed through the soil while direct current is passed through the measuring instrument. The ohmmeter embodies two coils, mounted at a fixed angle to one another on a common axle, moving in the field of a permanent magnet. A current proportional to the total current flowing in the testing circuit passes through the current coil, while the potential coil carries a current proportional to the potential drop across the resistance under test. The coils are so wound that the resulting forces oppose one another.

The final position of the moving coils, and hence that of the pointer, depends on the ratio of the potential drop to the total current, and the instrument is therefore a true ohmmeter giving readings in ohms, which are independent of the applied voltage.

The connections are shown in Figs. 2 and 3. Direct current from the generator passes through the current coil of the ohmmeter to a rotating current reverser driven from the generator handle. Alternating current is thus delivered to the current terminals (the common terminal and C in the diagram) of the instrument, which are connected to the contact under test and to the "current" temporary earth connection. The potential coil of the ohmmeter obtains its supply from the potential terminals (the common terminal and the terminal P in the diagram), the latter being connected to the "potential" temporary earth connection. Since this supply is taken from the "soil" section of the current circuit and is therefore alternating, it must be made unidirectional before passing through the potential coil. A commutator mounted on the same shaft as the main current reverser, and synchronized with it, is therefore interposed as a rectifier between the potential terminals and the potential coil.

In this manner the current and potential coils of the ohmmeter are both supplied with direct current, and the "soil" section of the testing circuit is supplied with alternating current.

WATER HEATING

Generally speaking, there are two possible methods of providing a supply of hot water by electricity for domestic purposes. The first method consists of a conversion of the existing hot-water system by means of an immersion heater or circulator. Where there is no existing hot-water system or where it is unsuitable for conversion, use must be made of the self-contained storage heater. Another use for the self-contained heater is to be found in situations where a supply of hot water is required at one point only. Before installing any type of electric water-heater it is necessary to very carefully check the existing piping if satisfactory results are to be obtained.

Immersion Heaters.—Immersion heaters are usually fitted into the existing hot-water tank about 3 inches from the bottom in a horizontal position. They may be controlled by a thermostat or by means of a three-heat switch. If thermostatic control is adopted it is important that the hot-water tank should be effectively "lagged" or heat insulated. Thermostatic control will provide a constant supply of hot water without attention and is, therefore, to be recommended where conditions are suitable. Three-heat control should be adopted where it is impossible to effectively "lag" the tank or where the heater is only to be used occasionally.

Circulators.—The circulator really consists of an immersion heater arranged for vertical mounting. Sometimes the elements are enclosed in a tube having an open end at the bottom and outlet holes at the top. The circulator is usually fitted through the top of the tank and it should be of sufficient length to reach within a few inches of the bottom. The value of the circulator is that a small quantity of water is raised to full temperature within a short while of switching on. The heated water rising through the circulating tube to the top of the tank passing in the process over the whole length of the element which raises the temperature of the water to a useful degree. It should be noted, however, that the time taken to raise a given quantity of water through a given temperature rise is the same whether an immersion heater or circulator is used, providing, of course, the loading of the heaters is the same.

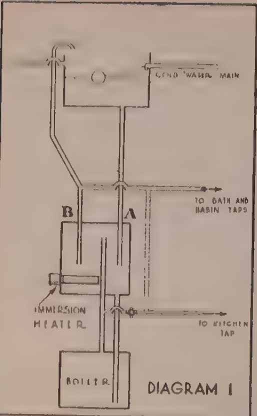


DIAGRAM 1

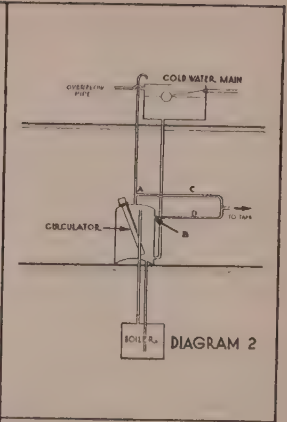


DIAGRAM 2

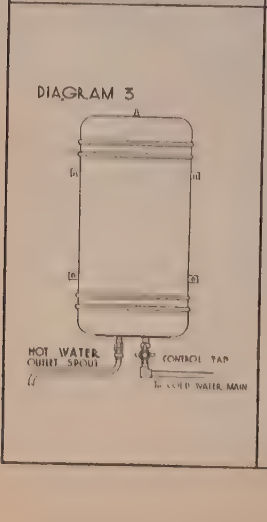


DIAGRAM 3

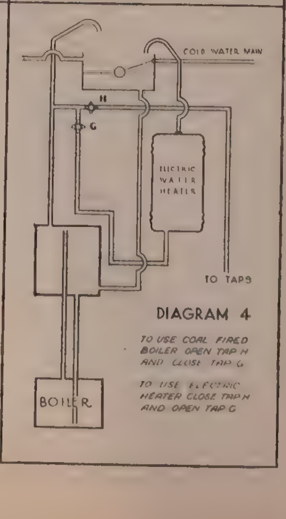


DIAGRAM 4

TO USE COAL FIRED BOILER OPEN TAP H AND CLOSE TAP G

TO USE ELECTRIC HEATER CLOSE TAP H AND OPEN TAP G

Owing to the quick heating of small quantities of water the circulator is very suitable for hand control. Circulators are available for both top and bottom entry.

Necessary Pipe Alterations.—As mentioned previously, the most important point in designing an immersion heater or circulator installation is to make certain that the existing hot-water installation is suitable for conversion. The chief difference between a system heated by a coal- or coke-fired boiler and that heated by means of an immersion heater is the position of the source of heat. The boiler is normally situated below the hot-water tank and the heated water is fed into the tank through the flow-pipe. An immersion heater is actually fitted in the tank where the hottest water will always be at the top. It is important, therefore, that the hot-water taps should be fed from the top of the tank. In Diagram 1 some of the faults commonly found in hot-water installations are shown. There are three primary faults shown, which must be removed if satisfactory results are to be obtained. The kitchen tap is fed from the boiler flow-pipe and consequently will not, when the electric heater is in use, give a supply of water at the full possible temperature. In fact, the water may be practically cold. It is obvious that water would be drawn from both the boiler and the tank, but as the water in the boiler is cold the water actually drawn at the tap would be a mixture of hot water from the tank and cold water from the boiler. Sometimes all the taps in an installation are fed from the boiler flow-pipe and it is then necessary to alter them so that they are fed from the top of the tank. The alteration to the piping to the kitchen tap is shown by a dotted line in Diagram 1. The original pipe must be disconnected at the point marked with a cross.

It will be noticed that the expansion pipe B is taken some little way into the hot-water tank. Not only does this mean that water is drawn from a position too low in the tank but it is possible for an air-lock to occur at the top of the tank which may result in damage to the heater. The expansion pipe should finish flush with the top of the tank.

Another possible source of trouble is the cold-water inlet A which has not been taken low enough into the tank. When the cold water enters the hot tank through this short pipe it causes considerable mixing with the contained hot water, with the result that the full contents of the tank will not be available at the highest possible temperature. Sometimes,

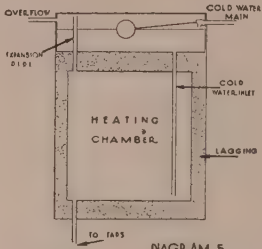


DIAGRAM 5

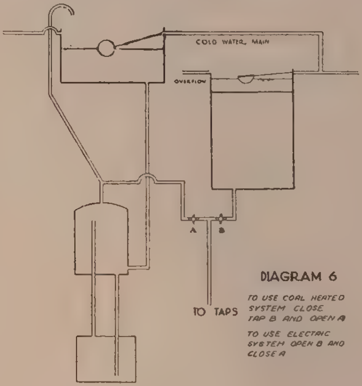


DIAGRAM 6

TO USE COAL HEATED SYSTEM CLOSE TAP B AND OPEN A

TO USE ELECTRIC SYSTEM OPEN B AND CLOSE A

when a circulator has been fitted to a tank, trouble will be experienced by the premature cutting out of the thermostat. Very often this is due to the tank not standing level, with the result that an air lock occurs at the top on the opposite side to the point where the expansion pipe is connected. Generally speaking, a circulator would be fitted on this side owing to the larger space available and, if the air lock is sufficiently great, the hot-water outlet ports (or holes) on the circulating tube will be above the water-level. This effectively prevents circulation, so that the thermostat cuts out when the water in the circulating tube has reached the set temperature.

There are a large number of hot-water installations in which a secondary circulation is employed in order to reduce the amount of dead water that would otherwise have to be drawn off before hot water was available. In Diagram 2 a typical lay-out of such an installation is shown. It will be seen that the whole time there is a difference in temperature between the points A and B there will be a circulation from the tank along the pipe C and back to the tank through the pipe D. As the loss of heat from such a pipe as this situated in the roof, as it usually is, might under average conditions be 1·5 B.T.U.s per degree difference in temperature per square foot of pipe surface; thus 30 feet of 1-inch pipe (and both flow and return must be taken into consideration), having a surface of 10·4 square feet, would lose almost 500 watts per hour with a water temperature of 160° F.

The loss of heat from any object depends on the nature of its surface and the number of changes of the air surrounding it. Apart from the question of difference of temperature it is, therefore, impossible to lay down hard and fast rules for the calculation of the loss of heat. A galvanized-iron hot-water tank situated in a linen cupboard with the door closed loses approximately 1 B.T.U. per square foot of surface per degree F. difference in temperature. This result was obtained from a number of actual tests carried out under working conditions. A rough formula for the calculation is, therefore, as follows:

Loss of heat in kilowatt-hours

$$= \frac{\text{square feet of surface} \times \text{temperature difference degrees F}}{3412}.$$

It must be used with great caution, for in some situations it is possible that the actual loss may be double the calculated figure. If a tank is "lagged" the formula may be

adjusted to include the heat-insulating properties of the "lagging" material.

Loss of heat in kilowatt-hours

$$= \frac{\frac{K}{t} \times \text{square feet} \times \text{temperature difference degrees F.}}{3412}.$$

Where K is the conductivity of the "lagging" material and t is the thickness in inches. The figure for K should be obtained from the manufacturers of the insulating material, but, in any case, it should be doubled to allow a margin of safety.

The formula for calculating the time taken to heat a given quantity of water through a given temperature rise with a given loading is:

$$\text{Time} = \frac{\text{gallons} \times \text{temperature rise degrees F.}}{341 \times \text{Percentage efficiency} \times \text{kilowatts}}.$$

The calculation of any other unknown quantity may be made by adjusting the above formula. For reference purposes the various formulæ are set down below.

Kilowatts required to raise temperature of water through given temperature rise:

$$\frac{\text{gallons} \times \text{temperature rise degrees F.}}{341 \times \text{percentage efficiency}}.$$

Kilowatts required to raise given quantity of water through given temperature rise in a given time:

$$\frac{\text{gallons} \times \text{temperature rise degrees F.}}{341 \times \text{time in hours} \times \text{percentage efficiency}}.$$

Temperature rise per hour with a given loading acting on a given quantity of water:

$$\frac{\text{kilowatts} \times 341 \times \text{percentage efficiency}}{\text{gallons}}.$$

Temperature rise after a given time for a given loading acting on a given quantity of water:

$$\frac{\text{kilowatts} \times 341 \times \text{time in hours}}{\text{gallons}}.$$

Gallons per hour raised through given temperature rise with given loading:

$$\frac{341 \times \text{kilowatts}}{\text{temperature rise degrees F.}}.$$

If an efficiency of 88 per cent. is assumed it is possible to simplify some of the above formulæ. This figure substituted in the first formula gives

Time in hours

$$= \frac{\text{gallons} \times \text{temperature rise degrees F.}}{\text{kilowatts} \times 300} \text{ approx.}$$

which is very easily remembered.

Useful Temperatures and Calculations

Cold water	40° to 50° F.
Comfortable room temperature .	60° to 70° F.
Bath water	105° to 110° F.
Dish washing	120° to 140° F.
Scalding water	150° F.
Boiling water	212° F.

The calculations necessary in order to obtain the capacity of a tank or cylinder are as follows:

Rectangular Tank:

$$\text{Gallons} = \frac{\text{height} \times \text{width} \times \text{depth}}{276}.$$

Cylindrical Tank:

$$\text{Gallons} = \frac{\text{diameter} \times \text{diameter} \times 0{\cdot}78 \times \text{depth}}{276}.$$

All the above measurements are in inches.

Self-Contained Storage Heaters.—There are three distinct types of self-contained storage heaters in general use and each is designed to meet certain conditions.

The Non-Pressure type heater is designed to supply hot water to one position only through a permanently open outlet, the control of the flow of water being achieved by means of a tap or stopcock inserted in the inlet pipe. This type of heater may be connected direct to the water main, subject of course to the water company's restrictions as to maximum capacity. The 1½- and 3-gallon storage heater are very suitable for fitting over the kitchen sink. Even when an immersion heater is fitted it is sometimes an economy to use a self-contained unit to supply points which are some distance from the hot-water tank. Diagram 3 shows the water connections to a non-pressure type storage heater.

The Pressure type heater is suitable for connection direct to a low-pressure cold-water supply such as would be available from the ordinary domestic cold-water cistern. It may be arranged to supply any number of taps compatible with its capacity. Another use for the pressure type heater is to

provide an alternative supply of hot water to that provided by the coal- or coke-fired boiler. Such an arrangement is shown in Diagram 4.

The Cistern type heater, as its name implies, has a small cold-water cistern fitted above the heating chamber. It is really a complete hot-water system in one outer case. The cistern type heater may be connected direct to the cold-water main and it can be arranged to supply any number of taps. It must, of course, be fitted at a position above the highest tap it is to feed. As an alternative supply it may be interconnected into the existing hot-water system. Diagrams 5 and 6 show cistern type heaters arranged as described above.

The consumption of electric water heaters depends to a large extent on the quantity of hot water used. For purposes of comparison some average figures are given below.

Immersion heaters or circulators	40 to 70 units per week
1½- and 3-gallon storage heaters	15 to 30 ,, ,, ,,
12-gallon storage heaters . .	4 to 5 units per bath
20-gallon storage heaters . .	50 to 80 units per week

SPACE HEATING

The development of domestic space heating has not yet reached the point achieved by water heating. This is probably due to the comparatively high cost of electricity in most districts and, it must be admitted, the problem has not yet been tackled in a scientific manner. In fact, there is a serious lack of knowledge on this subject amongst the staff of the majority of supply authorities and contractors.

One of the first essentials for domestic space heating is the speed at which the effects of the heater will be felt. This applies more especially to living-rooms and bedrooms, while a totally different set of conditions have to be met in the hall, landings and passages. The only practical method by which the effect of heat may be obtained quickly is by means of radiant heaters. There are already available on the market, reflector type fires having a high degree of radiant efficiency. These fires have highly polished parabolic reflectors so arranged that an average room is flooded with radiant heat. In some fires side reflectors are fitted which add greatly to their effect. With a correctly designed reflector type fire it is possible to heat a room 11 feet 6 inches by 13 feet 6 inches

by 8 feet with a maximum loading of 1,250 watts. If the loading required to heat such a room is calculated by one of the usual formulæ the loading apparently required is considerably higher. Thus: $1{,}242 \times 0{\cdot}02 \times 2 \times 30 = 1{,}490{\cdot}4$ B.T.U.s, while the loss of heat in the example taken is:—

60 square feet glass windows	1,854	B.T.U.s
32 square feet outside wall	316	,,
155 square feet ceiling	395	,,
155 square feet floor	8	,,
200 square feet inside walls	880	,,
108 square feet 9-inch inside wall	534	,,

giving a total of 3,987 B.T.U.s loss of heat per hour. The calculated loading is, therefore, nearly 2 kW. This figure would be correct if ordinary heaters were used which give off a large proportion of their heat by air convection currents. It will be seen that if a room of average size can be effectively heated with a maximum loading of 1,250 watts during the very cold weather, and a loading of, say, 750 watts during the warmer weather, the average consumption throughout the period heating is required is approximately one unit per hour. With current at ½*d.* per unit the cost per day would be about 6*d.*, a figure which compares very favourably with coal heating.

As mentioned previously, reflector type fires are not generally so suitable for heating halls, landings or passages. In these situations air heating is very effective, especially if reflector type heaters are being used in the living-rooms. The air heaters are best thermostatically controlled at a temperature between 50° and 60° F. according to individual tastes. Higher temperatures than 60° F. are quite unnecessary and tend to make a house stuffy. It is excessive air temperatures which give rise to this complaint often made about central heating. A good average temperature for a hall or landing is 55° F. and the thermostat should be arranged to cut out at this temperature. When air heating is being considered it is necessary to know the approximate loss of heat likely to take place through walls, etc. The following coefficients give the loss in B.T.U.s per square foot of surface per degree F. per hour:—

9-inch plastered wall	0·33
4½-inch plastered wall	0·44
Lath and plaster ceiling with wood floor above (cold air above)	0·17
Ditto (with cold air below)	0·07

Wood floor with air space and concrete foundations	0·05
Tiled boarded roof	0·35
Tiled roof and lath and plaster ceiling . . .	0·24
Single glass windows	1·03

The amount of heat required to raise the temperature of one cubic foot of air one degree F. is approximately 0·02 B.T.U. A point to be remembered in calculating the loss of heat through a wall is the difference in temperature which will differ for each wall. For example, the difference in temperature between the inside and outside of an outside wall would probably be 30° F. in very cold weather, while the difference in temperature between the faces of an inside wall might only be a matter of 10° F., depending on the amount of heating in the other room or passage. In the case of bedrooms, the difference in temperature between a living-room below and the bedroom may be about 150°.

When calculating the heat required to raise the temperature of the air in a room it must be remembered that ventilation is continually going on and therefore the quantity of air to be heated is considerably more than the cubical contents of the room. It is usual to take two air changes per hour for a living-room and three air changes per hour for a hall. Where a room has a north aspect or is situated in a very windy position it is usual to add 10 per cent. to the calculated loss.

A good example of an air heater is to be found in the tubular heater which can be obtained in different lengths and is usually fitted along the skirting board. Even in a room heated by radiant heaters it is sometimes an advantage to make up for any undue loss of heat from, say, a window by fitting a length of tubular heater immediately below the window. It is possible that in a room having a large bay window that it will be impossible to arrange for a radiant heater to cover this particular position. A short length of heater will effectively overcome any difficulties in this respect.

When considering the heating of a public hall, etc., it must be remembered that the occupiers will develop a certain amount of heat and unless this is taken into consideration overheating may result. Naturally the amount of heat developed depends on the activity of the person, but a person at rest will develop about 300 B.T.U.'s per hour.

Where an installation is thermostatically controlled it is not necessary to consider this aspect, although it is possible that a slight reduction in the installed heating capacity may be achieved.

THEORY OF MEASURING INSTRUMENTS

Most instruments and meters are based on either the magnetic principle or that of electro-magnetic induction. In addition, there are a number of other instruments which make use of electrostatic, heating and chemical effects, each of these having a special application or applications.

AMMETERS AND VOLTMETERS

The normal instruments for measuring current and pressure are essentially the same in principle, as in most cases the deflection is proportional to the current passing through the instrument. These meters are, therefore, all ammeters, but in the case of a voltmeter the scale is such that the reading is proportional to the pressure across the instrument.

The types of instrument used are:

1. Moving iron (suitable for both A.C. and D.C.).
2. Permanent magnet moving coil (suitable for D.C. only).
3. Dynamometer type (moving coil) (suitable for both A.C. and D.C.).
4. Electrostatic (for A.C. and D.C. voltmeters).
5. Induction (suitable for A.C. only).
6. Hot wire (suitable for A.C. and D.C.).

Note.—The permanent-magnet moving-coil instrument can be used for A.C., provided a rectifier is incorporated, and this is described in another section.

Accuracy.

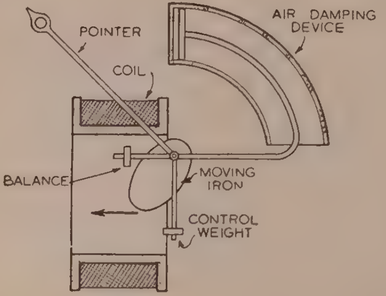
The accuracy of instruments used for measuring current and pressure will naturally vary with the type and quality of manufacture, and various grades of meters have been scheduled by the British Standards Institution. These are set out in the B.S.I. specification No. 89 (1929).

There are three grades of instruments:

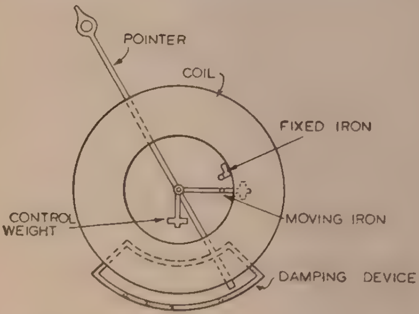
A. Substandard instruments.
B. First-grade instruments.
C. Second-grade instruments.

These grades enable an engineer to purchase instruments with an accuracy sufficient for the purpose for which the instrument is intended.

AMMETERS AND VOLTMETERS



MOVING-IRON INSTRUMENT (ATTRACTION TYPE)



MOVING-IRON INSTRUMENT (REPULSION TYPE)

For normal industrial use second-grade instruments are sufficiently accurate, and first-grade or substandard instruments are only purchased where a definite degree of accuracy is essential.

Instruments are grouped in these grades by virtue of the permissible errors which are set out in the specification.

MOVING-IRON INSTRUMENTS

This type of instrument is in general use in industry owing to its cheap first cost and its reliability. Although suitable for use on both A.C. and D.C. they have naturally been developed more for use on A.C.

There are two types of moving-coil instruments—the attraction type and the repulsion type.

The principle of operation is that a coil of wire carrying the current to be measured attracts or repels an armature of "soft" iron, which operates the indicating needle or pointer. With the attraction type the iron is drawn into the coil by means of the current; and in the repulsion type there are two pieces of iron inside the coil, one of these being fixed and the other movable. Both these are magnetized by the current and the repulsion between the two causes the movable unit to operate the pointer.

It will be seen, therefore, that the direction of current in the coil does not matter, making the instrument suitable for measuring any form of current, either D.C. or A.C., including rectified A.C. with any wave fall.

Causes of Error.

(*a*) *Stray Magnetic Fields*.—Owing to the fact that the deflection is proportional to the magnetic field inside the operating coil, magnetic fields due to any outside source will affect the deflection. Errors due to this are reduced by suitable magnetic screening of the mechanism.

(*b*) *Hysteresis*.—Even with the most suitable iron there is a certain amount of hysteresis, which causes readings to vary to some extent. Errors due to hysteresis are kept low by designing the armature so that it is not too large and has a fairly low flux density.

(*c*) *Frequency*.—Due to the reactance of the circuit changing the frequency, different readings will be obtained on different frequencies and there is also an effect due to eddy currents.

As frequency is now standardized this is not important, and where necessary a condenser can be used to make the instrument practically independent of frequency.

PERMANENT-MAGNET MOVING-COIL INSTRUMENTS

These are essentially D.C. instruments and they will not operate on alternating current. They can, however, be used for A.C. measurements by incorporating a rectifier in the circuit so that only unidirectional current is passed through the instrument. This subject is dealt with on a later page.

The operation of a moving-coil instrument will be seen from the diagram. By means of a suitably designed permanent magnet and a soft iron cylinder between the poles a circular air-gap is formed through which a pivoted coil can move. This pivoted coil carries the current to be measured (or some proportion of it), and as the field is uniform in the air-gap the torque will be proportional to the current. The deflection is controlled by means of a torsion spring with suitable adjustment device and the current is taken to the moving coil by means of these or other coil springs.

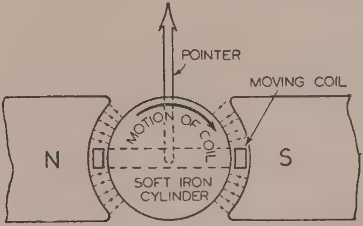
Permanent-magnet moving-coil instruments are only suitable for small currents for actuating purposes, and thus both shunts and series resistances are used to a fair extent. Stock instruments usually have a full scale current of 0·015 amp. with a volt-drop of 0·075 volt. From this it will be seen that the total resistance of the operating circuit is in the nature of 5 ohms.

The actual calculations for values of shunts and series resistances is dealt with on a previous page, and an example is included of an instrument of this type.

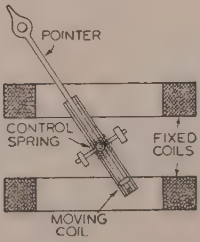
Damping is obtained by the eddy currents induced in the metal former which is used for the moving coil. Owing to the strong magnetic field due to the permanent magnet, these instruments have a high torque and are thus ideal for use on currents of low amperage. They are used extensively for milliampmeters, but for D.C. measurements generally they have many advantages over moving-iron instruments although they are much more expensive. The scale is uniform and can be made to extend over a fairly large arc. The power consumption is low and the instrument is practically unaffected by stray fields or hysteresis errors.

The only serious errors are due to friction and temperature, but it must be remembered that a good permanent magnet is essential for a long accurate life and the instrument should be tested periodically to make sure that the magnet has not weakened.

AMMETERS AND VOLTMETERS



PERMANENT-MAGNET MOVING-COIL INSTRUMENT



DYNAMOMETER MOVING COIL INSTRUMENT

DYNAMOMETER MOVING-COIL INSTRUMENTS

Instead of the permanent magnet of the previous type of moving-coil instrument, the necessary magnetic field may be set up by passing the current through fixed coils as shown in the diagram. There are thus two sets of coils—one fixed and one pivoted—the torque being proportional to the square of the current, making the instrument suitable for either D.C. or A.C.

In the case of an ammeter, the two systems are usually connected in parallel with suitable resistances, and in the case of a voltmeter they are in series. The leads to the moving coil are in the form of coil springs, which also act as the torque control, and in this case damping has to be provided by some type of damping device such as an aluminium disc with a braking magnet.

Owing to the necessity of keeping the current in the moving coil low the torque obtainable may be small, and these instruments are not used to any extent for general industrial purposes. For D.C. they are inferior to the permanent-magnet type, and although they will operate on A.C. their cost usually rules them out. When used care must be taken to see that they are not affected by stray magnetic fields.

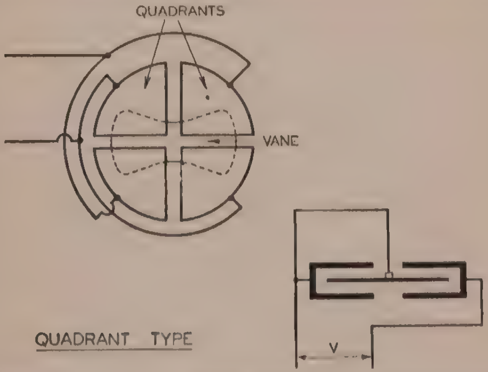
The dynamometer instrument is, however, much used for wattmeters, and its use for this purpose is described later.

ELECTROSTATIC VOLTMETERS

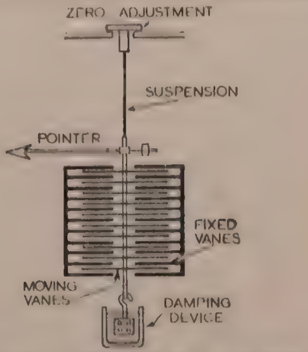
Electrostatic instruments are confined to voltmeters as they operate by means of the attraction or repulsion of two charged bodies. They have certain applications in the laboratory as they are unaffected by conditions and variations which give rise to errors in many other instruments. These include hysteresis and eddy current errors, errors due to variations in frequency and wave form which do not cause incorrect readings with electrostatic instruments.

For ordinary voltages the torque is small and multi-disc instruments have to be used. On this account, however, they are ideal for measuring high voltages and form practically the only method of indicating the pressure direct where the voltage is in the region of a hundred kilovolts and over.

ELECTROSTATIC VOLTMETERS

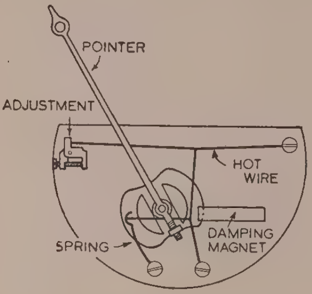


QUADRANT TYPE

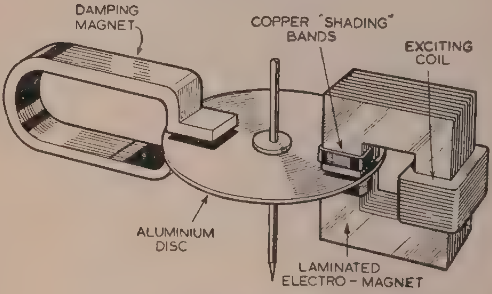


MULTIVANE ELECTROSTATIC VOLTMETER

AMMETERS AND VOLTMETERS



HOT-WIRE INSTRUMENT



PRINCIPLE OF THE SHADED POLE TYPE INDUCTION INSTRUMENT

For low voltages of from 400 to a few thousand volts the *quadrant* type is used, the principle being as in the diagram. The moving vane is pivoted and is either repelled or attracted or both by the charges on the vane and the quadrants—these charges being proportional to the potential due to their connection to the supply.

In commercial models several sets of vanes are used in parallel to obtain sufficient torque, and the general arrangement is as shown on the opposite page.

Voltages of 100,000 volts and over are measured by means of two shaped discs with an air-space between them, one disc being fixed and the other movable axially. By means of a balance the force between the two is measured and the scale of the balance marked in kilovolts. These high-tension voltmeters are not, of course, accurate to a degree that makes them suitable for indicating line voltages or for switchboard purposes. They are, however, ideal for testing purposes where cables and other apparatus is subject to high-voltage and destruction tests. In this case they form a visual indication of the applied pressure and are a check on the value indicated by the instruments on the voltage *stepping-up* apparatus.

Electrostatic instruments for laboratory use are termed *electrometers* and are usually of the suspension type with mirror-operated scales.

As these instruments do not consume any power whatever, they have the advantage that they do not affect the state of any circuit to which they are connected. There is a very small current flowing on A.C., but this is negligible in nearly all cases.

INDUCTION INSTRUMENTS

These instruments, which will function only on A.C., may be used for ammeters and voltmeters, but their applications for these two quantities are much less than for wattmeters and energy meters—these applications being described fully elsewhere.

In all induction instruments the torque of the moving system is due to the reaction of a flux produced by the current to be measured on the eddy currents flowing in a metal disc or cylinder, this latter flux also being due to the current but arranged to be out of phase with the former flux.

There are two methods by which these fluxes are obtained. With a cylindrical rotor two sets of coils can be used at right angles, or with a disc rotor the shaded pole principle is used, an alternative being the use of two magnetic fields acting on the disc.

Although extremely simple, with no connections to the rotor, these instruments have many disadvantages which prevent their use for general purposes as ammeters and voltmeters. The points in their favour are a long scale, good damping and freedom from stray field effects. Their disadvantages include fairly serious errors due to variation in frequency and temperature, high power consumption, and their high cost. The former may be reduced by suitable compensation, but in ordinary commercial instruments the variation is still important, although first-grade instruments can be supplied if required.

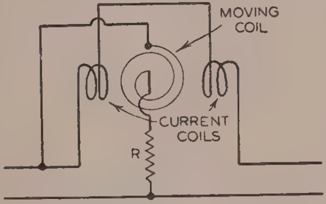
WATTMETERS

Dynamometer Wattmeters.—This type of wattmeter will give correct readings both on D.C. and A.C., and consists of a stationary circuit carrying the current and a moving circuit representing the pressure of the circuit. For laboratory instruments the meter may be either of the suspended coil or pivoted coil type. The former is used as a standard wattmeter, but the pivoted coil has a much wider scope as it is suitable for direct indicating.

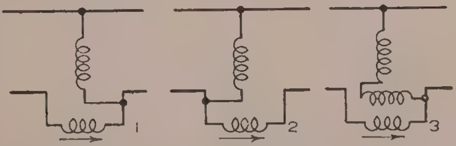
For accurate measurements it is necessary to compensate for the flow of current in the other circuit by adding a compensating winding to the current circuit. This will be seen from the diagram opposite, where the connections (1) and (2) will introduce errors due to the extra current in the current coil in (1) and the volt-drop in the current coil in (2). It will be seen that the arrangement in (3) overcomes these errors.

In addition to errors caused by the inductance of the pressure circuit, dynamometer wattmeters are affected by stray fields. This is true for both D.C. and A.C. measurements, but on A.C. only alternating current stray fields affect readings. This effect is avoided by using astatic construction for laboratory instruments and by shielding for portable types. The use of a nickel-iron of high permeability has enabled modern wattmeters to be practically unaffected by stray fields in ordinary careful use.

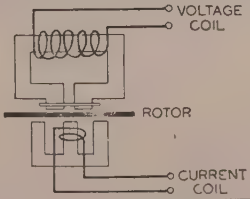
WATTMETERS



DYNAMOMETER TYPE WATTMETER

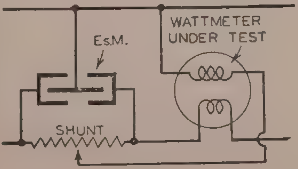


UNCOMPENSATED (1&2) AND COMPENSATED WATTMETERS



INDUCTION TYPE WATTMETER

CONSTRUCTION AND PRINCIPLE OF OPERATION SIMILAR TO ENERGY METER



ELECTROSTATIC WATTMETER USED FOR CALIBRATION PURPOSES

When purchasing wattmeters of this type it is desirable to see that a high factor of safety is used as regards the rating of the coils of the instrument. This is desirable from the point of possible overload on any of the ranges of a multi-range instrument, but it also enables the indication to be made towards full-scale even at low power-factors.

For 3-phase wattmeters, adequate shielding between the two sections is necessary, and 3-phase wattmeters do not give the same accuracy as single-phase models.

Induction Wattmeters.—These can only be used on A.C. and are similar to energy meters of the induction type, the rotating disc in this case operating against a torsion spring. The two circuits are similar to the induction energy meter and the connections are as shown on page 231.

Although affected by variations in temperature and frequency, the former is compensated for by the variation in resistance of the rotating disc (which is opposite in effect to the effect on the windings), and the latter does not vary considerably with the variations in frequency which usually obtain. Induction wattmeters must not, of course, be used on any other frequency than that for which they are designed unless specially arranged with suitable tappings.

The general construction of induction wattmeters renders them reliable and robust. They have a definite advantage for switchboard use in that the scale may be over an arc of 300° or so. As with dynamometer types, the 3-phase 2-element wattmeter is not as accurate as the single-phase type.

Three-phase Wattmeters.—These operate on the two wattmeter principle, the two rotors being mechanically coupled to give the sum of the torques of the two elements. As already stated, it is important to avoid any interference between the two sections, and there are several methods of preventing this. One is to use a compensating resistance in the connections to the pressure coils, and another, due to Drysdale, is to mount the two moving coils (of the dynamometer type) at right angles.

SHUNTS AND SERIES RESISTANCES

THE control or reduction of the actual currents flowing in the various circuits of an instrument or meter may be obtained either by means of resistances (for both D.C. and A.C.) or by the use of instrument transformers (A.C. only).

Shunts.—Non-inductive resistances for increasing the range of ammeters are termed shunts and are connected as shown on page 222. The relative values to give any required result can be seen as follows, the symbols being marked on the diagram:

Let R = resistance of ammeter
r = resistance of shunt
I = total current in circuit
i_a = current in ammeter
i_s = current in shunt.

We have $I = i_a + i_s$, and as the volt-drop across the meter and the shunt are the same we get

$$i_a R = i_s r$$

$$\therefore\ i_a = i_s \frac{r}{R} = I \frac{r}{R + r}$$

or

$$I = i_a \frac{R + r}{r}$$

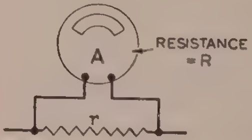
$$= i_a \left(\frac{R}{r} + 1 \right)$$

The expression $\left(\frac{R}{r} + 1 \right)$ is termed the *multiplying power* of the shunt.

As an example, take the case of a meter reading to 5 amps. having a resistance of 0·02 ohm. Find a suitable shunt for use on circuits up to 100 amps.

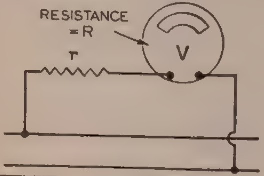
As the total current has to be $\frac{100}{5} = 20$ times that through the meter, the shunt must carry 19 times. Thus its resistance must be $\frac{1}{19}$ that of the meter, giving a shunt whose resistance is $\frac{0{\cdot}02}{19}$ or 0·00105 ohm.

SHUNTS AND RESISTANCES



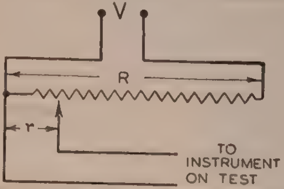
AMMETER SHUNT

MULTIPLYING POWER
$= \frac{R}{r} + 1$



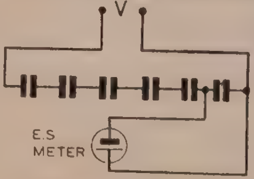
SERIES RESISTANCE FOR VOLTMETER

MULTIPLYING POWER
$= \frac{R+r}{R}$



VOLTAGE DIVIDER

RATIO $= \frac{R}{r}$



CONDENSER VOLTAGE DIVIDER

Series Resistances.—In the case of voltmeters it is often impracticable to allow the whole voltage to be taken to the coil or coils of the instrument. For instance, in the case of a moving-coil voltmeter the current in the moving coil will be in the nature of 0·01 amp. and its resistance will probably be only 100 ohms. If this instrument is to be used for, say, 100 volts, a series resistance will be essential—connected as shown in the diagram opposite.

The relation between total voltage and that of the meter is simple as the two voltages are in series. Thus in the above case the full-scale current will be 0·01 amp., so that the total resistance for 100 volts will have to be $\frac{100}{0 \cdot 01}$ or 10,000 ohms. If the resistance of the meter circuit and its connecting leads is 100 ohms, then the added or series resistance must be $10{,}000 - 100 = 9{,}900$ ohms.

The multiplying power is the ratio between the total voltage across the instrument. If

$$\text{R} = \text{resistance of meter}$$
$$r = \text{value of series resistance}$$

then multiplying power $= \frac{\text{R} + r}{\text{R}}$.

Construction of Shunts and Series Resistances.—Shunts and resistances usually consist of manganin strips soldered to terminal blocks at each end and arranged so that air will circulate between the strips for cooling.

Voltage Dividers.—Voltage dividers or volt-boxes can only be used with accuracy with testing equipment or measuring instruments which do not take any current, or with electrostatic instruments. The former state of affairs refers to tests using the " null " or zero deflection for balancing or taking a reading while the electrostatic meter actually does not take any current.

The principle of the voltage divider is seen on page 222. The voltage to be measured is connected across a resistance R and the connections are taken off some fraction of this resistance as shown. The ratio is given by $\frac{\text{R}}{r}$.

A similar arrangement is possible with condensers for use with electrostatic instruments, but the method is somewhat complicated owing to the variation in capacity of the instrument as the vane or vanes move.

ENERGY METERS

KILOWATT-HOUR meters were developed in the early days of the Supply Industry because it was most important to be able to accurately measure the energy supplied to a consumer. Many types were invented and several principles of operation were utilized, but in all cases the devices are based on the fact that the rate of registration can be made closely proportional to the power being supplied. Since energy is the integral of power with respect to time it will be appreciated why the registration is proportional to the energy supplied and why electricity meters are called integrating meters.

The various principles employed are as follows :

Electrolytic Meters.—The direct current being measured is passed through an electrolyte, and since the rate of chemical action is proportional to the current (Faraday's Law), then the fall in level of the electrolyte or the amount of material deposited on the cathode is a measure of the ampere-hours supplied. If the voltage is assumed to be constant at a certain stated value, then the ampere-hours are also a measure of the kilowatt hours supplied and the meter is usually calibrated in terms of kWh on this basis.

Fig. 1 illustrates one of the two types of this class of meter. The Bastian meter is now obsolete owing to the practical difficulties of maintaining it. It is interesting to note that the Reason Manufacturing Company manufacture a rectifier to enable their electrolytic meter to measure ampere-hours on A.C. circuits, providing the wave shape is sinusoidal.

Mercury Motor Meters.—The direct current is passed through a copper disc in the region where it is cut by the magnetic flux of a strong permanent magnet, and the consequent torque, which is proportional to the current, causes the disc to revolve. The current is led in and out of the copper disc by immersing the disc in a bath of mercury and placing suitable electrodes at two points of the bath wall.

The motion of the disc is controlled by the eddy current braking effect of the copper disc cutting the flux of the permanent magnet or magnets. Consequently the speed of the

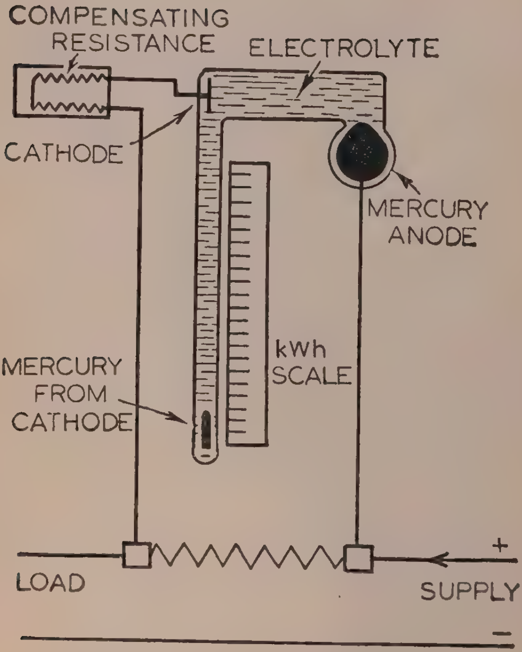


Fig. 1.—Principle of the Reason Meter.

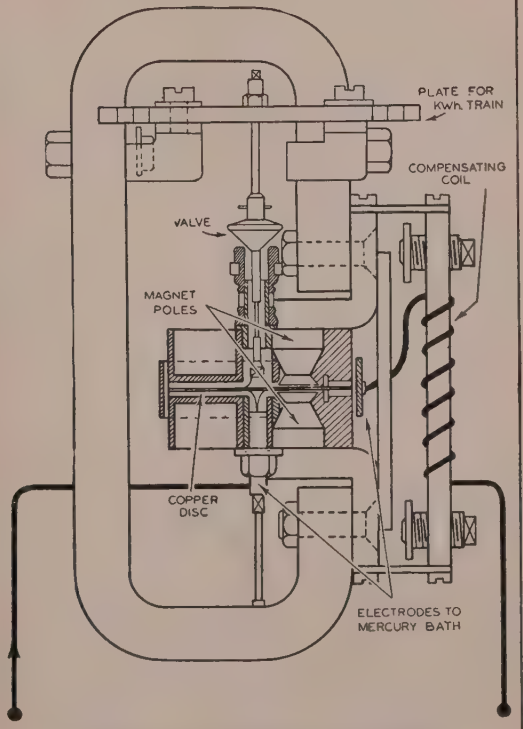


FIG 2 THE SINGLE MAGNET TYPE OF MERCURY MOTOR AMPERE-HOUR METER

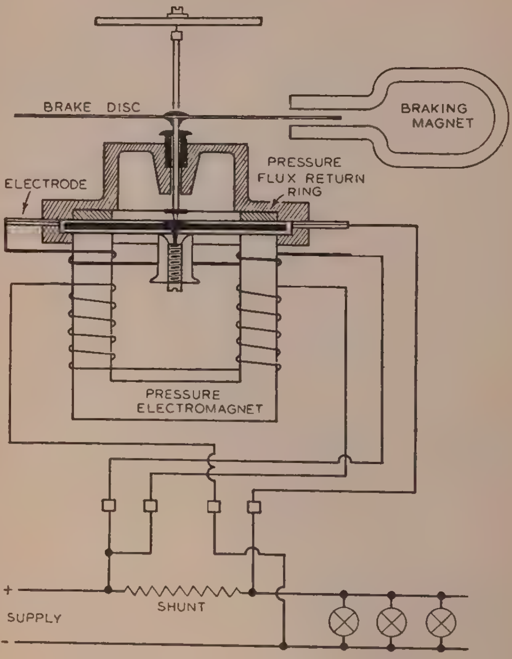


FIG 3 MERCURY MOTOR WATT-HOUR METER

disc is closely proportional to the current passing through the meter because the braking torque is proportional to the disc speed since the braking flux is constant.

It should be mentioned here that all motor meters make use of the eddy current brake owing to its ideal property of being proportional to the disc speed. Every motor, however, possesses some friction and this is usually the greatest difficulty in making meters accurate on all loads. Unfortunately the mercury motor meter cannot be easily compensated for the effect of friction and thus its performance on low loads is not very efficient.

Fig. 2 gives details of a single magnet type. Fig. 3 illustrates the mercury motor watt-hour meter in which the permanent driving magnet is replaced by an electro-magnet energized from the voltage being measured. The braking magnet in this meter is quite separate and has its own disc on which to operate.

Commutator Motor Meters.—These work on just the same principle as the ordinary commutator motor, but their construction is rather different on account of the need for reducing friction to a minimum and for keeping the driving torque proportional to the power being measured. Fig. 4 indicates the chief features of the ampere-hour meter type, whilst Fig. 5 indicates those of the watt-hour meter. The coils (which are inside the aluminium disc) are of the pancake pattern for the A.H.M. owing to the magnet gap having to be narrow. The aluminium disc is used for eddy current braking purposes.

Although it is possible to use the commutator W.H.M. on A.C. as well as D.C. it is very rare to do so on account of various practical and financial disadvantages as compared with the induction W.H.M. Commutator meters, however, whether A.H. or W.H., have not been very popular on account of maintenance difficulties, and furthermore the Electricity Commissioners have now disapproved of them unless they can satisfy B.S.S. No. 37.

Pendulum Meters.—Fundamentally, the pendulum meter (see Fig. 6) consists of two similar pendulum clocks, the pendulums of which can be retarded or accelerated by the magnetic effect of the currents and voltages being measured. The two pendulums are geared together through a differential so as to make the planet wheel-arm of the differential run at a speed proportional to the difference in frequency of the

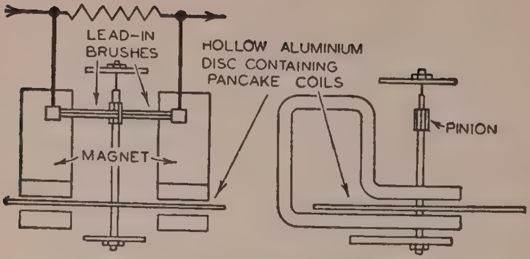


FIG. 4.—Commutator Ampere-hour Meter.

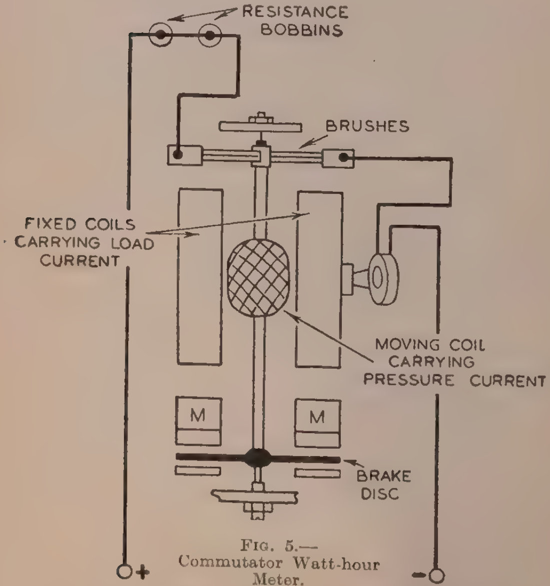


FIG. 5.—
Commutator Watt-hour
Meter.

(With acknowledgement to "Meter Engineering.")

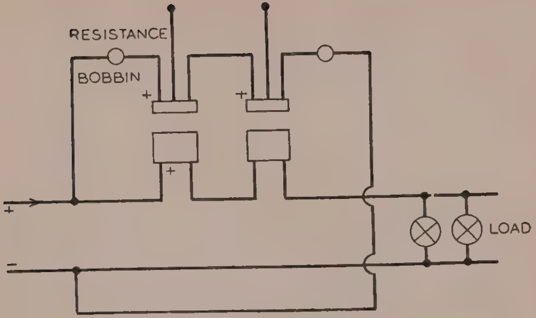


Fig. 6.—Electrical Circuits of a Two-Wire Pendulum Meter.

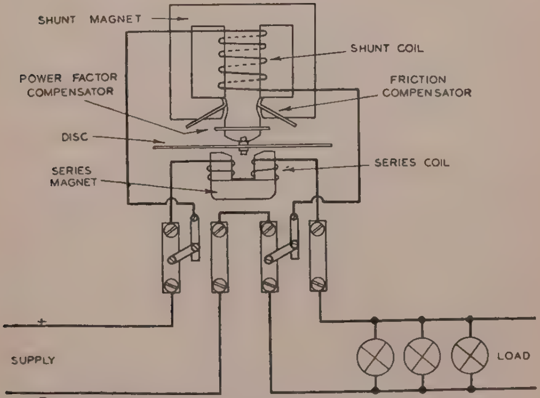


Fig. 7.—Electrical Circuits of a Typical Induction Meter.

PRINCIPLE OF INDUCTION METER FOR A. C.

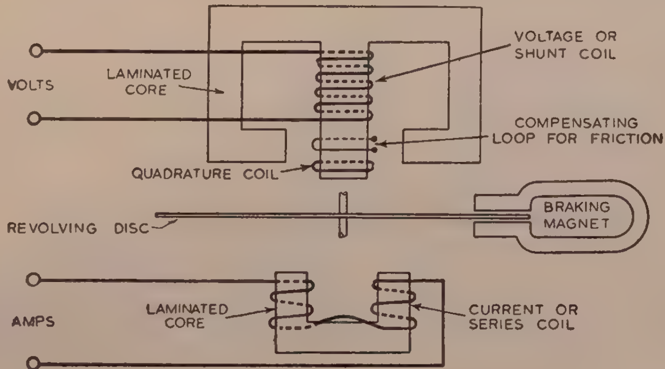


FIG 8 ESSENTIAL PARTS OF INDUCTION METER

two pendulums. The planet wheel arm in turn drives the kWh registering mechanism and thus the registration can be made proportional to the magnetic effects on the pendulums.

It will be seen from Fig. 6 that the pendulum carries a current proportional to the voltage, whilst the stationary coil under the pendulum carries the load current or a current proportional to the load current. (It is possible, however, to have the coils the other way round, but the above is the usual arrangement.) The magnetic fields set up by the coils repel or attract one another according to the way the coils are connected, and it is so arranged that when one pair attracts then the other pair repel. The degree of repulsion or attraction depends on the strengths of the magnetic fields and hence on the current and voltage being measured. Consequently one pendulum is sped up by an amount proportional to V.I. whilst the other is slowed down by this amount and thus the registration of the meter can be arranged to measure the kWh supplied.

The two pendulums, which are self-starting, are maintained by one driving spring acting through another differential gear. The driving spring is wound up every thirty seconds by means of an electro-magnet.

The meter is a true dynamometer and therefore it is suitable for use on A.C. or D.C., and owing to its inherent two-element construction it is also suitable for use on other circuits than the simple two-wire supply.

The reversing gear and commutator for simultaneously reversing the pendulum connections are necessary in order to overcome certain mechanical difficulties which would otherwise cause the meter to register on no load. The change-over takes place every 10 minutes, and it is for this reason that dial test periods should be multiples of twenty minutes.

Induction Meters.—The popular single-phase induction meter consists fundamentally of two electro-magnets, an aluminium disc, a revolution counter, and a brake magnet, as shown in Fig. 8. Fig. 7 shows the manner in which the coils are connected so as to create two A.C. fluxes cutting the disc—one proportional to the voltage and the other proportional to the current being measured. Each of these fluxes induces eddy currents in the disc. It is due to the interaction of the voltage flux with the eddy currents created by the current flux, and to the interaction of the current flux with the eddy currents created by the voltage

flux, that a torque is exerted on the disc, causing it to rotate. The purpose of the permanent magnet is simply to act as an eddy current brake on the motion of the disc so as to make the disc speed proportional to the power being measured. The voltage element is specially compensated by a quadrature adjuster so that the meter will be accurate at all power factors.

The induction meter is remarkable on account of the multiplicity of ways in which the electro-magnets and compensating devices can be arranged to give similar results, and on account of the high accuracy of measurement which can be achieved. Owing to the induction principle the mechanical construction is of the simplest possible type with a resulting freedom from frictional troubles and low maintenance requirements. Furthermore, the effect of friction is compensated by means of a special compensator which provides a driving torque irrespective of the load current.

In order to meter two- or three-phase supplies two or more elements are arranged so as to drive the same rotor system. The elements may operate on one disc or on separate discs mounted on a common shaft.

Testing of Meters.—Owing to test-room limitations it is not practicable to test meters under actual working conditions, and it is therefore customary to use phantom loads for testing purposes. It is usual for the current and voltage circuits to be supplied from independent sources and this enables the current to be supplied at a low voltage with consequent savings in energy, apparatus and test-room working conditions. So long as the conditions in the meter reproduce the working conditions it is obviously immaterial how the testing currents and voltages are derived.

D.C. meters are normally tested on battery circuits on account of their steady output, providing they are liberally rated. Fig. 9 indicates how the circuits are arranged.

Single-phase A.C. meters are usually tested on transformer circuits such as that shown on Fig. 10. A.C. circuits, however, vary in nature considerably according to the ideas of the designer, particularly polyphase testing circuits.

Meters vary widely in their detail testing requirements, but the general scheme is to test them at a high load, a low load and an intermediate load. Under the new regulations issued by the Electricity Commissioners the high load must be 100 per cent. full load (or 125 per cent. for A.C. meters), the low load must be 5 per cent. (or 10 per cent. for certain

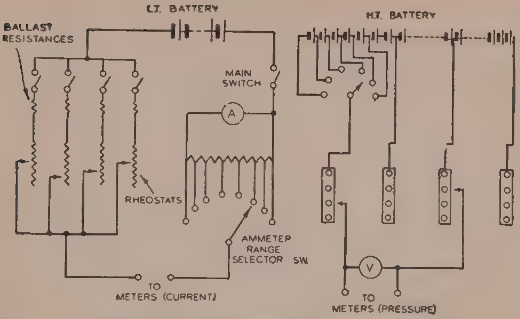


Fig. 9.—Testing Circuits for D.C. Meters.

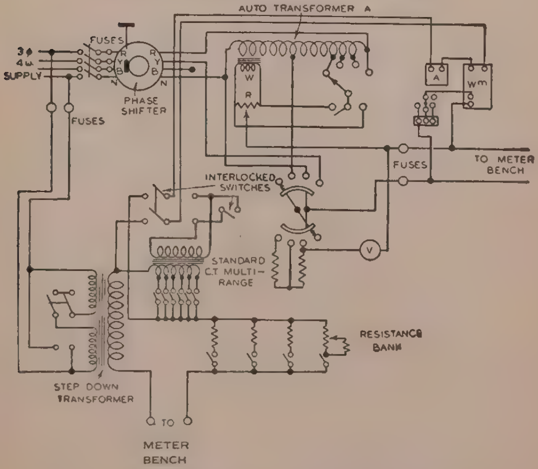


Fig. 10.—Single-Phase Meter Testing Circuit.

(Acknowledgement is made to "Meter Engineering.")

D.C. meters), whilst the intermediate load can be any intermediate value but is usually 25 per cent. of full load.

By testing these extreme loads the tester can be sure that the meter will be within the limits on all the other loads. After the meter has been calibrated and tested, it is given a dial test at full load (unless the previous errors have been determined by dial tests) to ensure that the registering mechanism is in perfect order.

Other routine tests which are made on the appropriate meters are:

1. *Starting Current Test.*—Motor meters must start and keep on running for at least 3 revs. on 1/100th load or 1/200th load.

2. *Creep Test.*—Watt-hour meters must not run more than a revolution on voltage only, and it is usual to raise the voltage to 10 per cent. in excess of normal for this test. Anti-creep devices are usually provided on watt-hour meters.

3. *Insulation Resistance.*—The I.R. of the winding to the case and the resistance between windings must be checked and should not be less than 5 megohms.

4. *Prepayment Mechanism.*—This is checked for accuracy of price per unit as well as for mechanical condition (e.g. meshing of the gear-wheels). Special P.P. meters such as the two-part tariff type require special tests depending on their construction.

5. *Balance Tests.*—Three-wire or polyphase meters require the elements to give equivalent effects and they must be tested to ensure this state of affairs.

NOTES

AUTOMATIC TEMPERATURE CONTROL

Thermostatic Switches.

Except in a few special instruments, thermostatic switches operate either on the bi-metal principle, or on the vapour-pressure principle. In the former, the unequal expansion of two metals forming a composite strip causes distortion, which actuates the switch. In the latter, changes of vapour-pressure in a system charged with a volatile liquid causes expansion or contraction of a metallic bellows, which operates the switch.

For currents up to 10 or 15 amperes A.C. or 5 amperes D.C. at 250 volts open switches with silver contacts are standard practice. For heavier duty a mercury-tube switch is used.

TYPICAL APPLICATIONS

Control of Space Heating.

(*a*) *Electric Heaters.*—Thermostat wired in series with the heaters (Fig. 1). If load is greater than the capacity of the thermostat, a relay or contactor must be used (Fig. 2).

(*b*) *Hot Water Circulation.*—Immersion thermostat in boiler to maintain constant water temperature by combustion control, e.g. motorized damper, and room thermostat to control room temperature by regulating circulation via a motorized valve.

Domestic Water Supply.

(*a*) *Electric Water Heater.*—Immersion thermostat maintains constant water temperature by switching electric heating elements.

(*b*) *Steam Calorifier.*—Pressure-stat to maintain constant steam pressure by combustion control, e.g. by motorized damper or magnetic gas fuel valve, and immersion thermostat in calorifier to maintain constant water temperature by regulating steam flow (Fig. 3).

THERMOSTATIC CONTROL

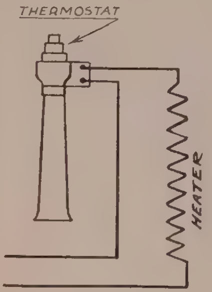


FIG. 1.

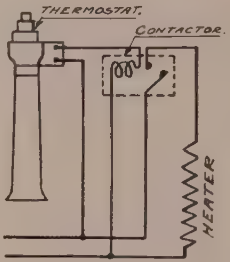


FIG 2.

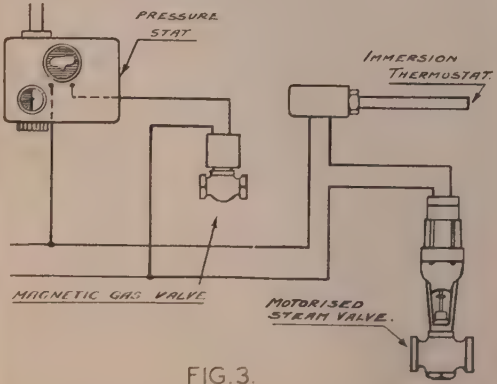


FIG. 3.

REFRIGERATION CONTROL.

(*a*) *Domestic Cabinet.*—Thermostat is sensitive to evaporator temperature, and switches off compressor when temperature falls.

(*b*) *Small Commercial Installation.*—Compressor motor controlled by thermostat sensitive to cabinet temperature or by pressure-stat operating upon suction pressure.

(*c*) *Multi-temperature Installations.*—Supply of refrigerant to each evaporator controlled by magnetic valve switched by cabinet thermostat. Secondary contacts on thermostats shut down compressor when all magnetic valves are shut (Fig. 5).

Hints on Installation and Maintenance of Thermostats

Thermostats should be located in positions which represent the mean temperature conditions of the space to be controlled. Positions well removed from doors or windows, exposed walls or other spots liable to abnormal conditions should be avoided.

Any thermometer used for checking the performance of a thermostat should be positioned as close as possible to the sensitive portion of the thermostat.

In installing thermostats of the vapour-pressure type having a sensitive bulb and capillary tube select a route for the capillary tube which gives the best protection from mechanical injury. Sharp bends in the tube should be avoided.

Thermostats incorporating mercury-tube switches should be fixed level and plumb. Otherwise the instrument may operate at a temperature a few degrees above or below the scale setting.

When ordering thermostats, give the manufacturer as much information as you can. Points to be specified include the temperature range required and the "differential," that is, the difference in temperature between the "cut-in" point and the "cut-out" point; whether the switch is to make or break circuit on a rise in temperature; and the voltage and current to be controlled.

Remember that although thermostats are often called upon to operate in unfavourable situations and under severe working conditions, they are none the less essentially scien-

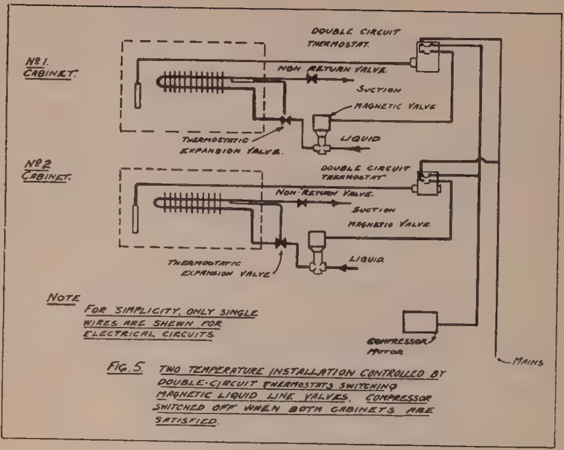


FIG. 5. TWO TEMPERATURE INSTALLATION CONTROLLED BY DOUBLE-CIRCUIT THERMOSTATS SWITCHING MAGNETIC LIQUID LINE VALVES. COMPRESSOR SWITCHED OFF WHEN BOTH CABINETS ARE SATISFIED.

THERMOSTAT CONTROL OF REFRIGERATOR

tific instruments of great accuracy. Thermostats of reputable make are of robust construction, but should be treated with due respect if they are to maintain their accuracy and reliability. Damp and dirt are the greatest enemies of satisfactory operation.

Industrial Applications

For temperatures up to about 400° F. thermostats suitable for immersion in heated vessels or to be embedded in heated masses such as the heated platens of moulding presses can be employed for controlling electric heaters or for regulating the flow of steam, air, water, gas or oil fuel by means of magnetic or motorized valves.

For higher temperature ranges, and particularly for furnace work, controlling pyrometers must be used. Thermo-electric pyrometers employ the E.M.F. generated when two junctions of dissimilar metals are maintained at different temperatures, and instruments are available for temperatures up to some 1,200 to 1,300° C. Change of temperature is indicated by the pointer of a moving-coil milli-voltmeter, and control is exercised by a mechanism, driven by a small electric motor, which actuates a switching device at intervals of a few seconds, in accordance with the position of the indicating pointer with respect to a predetermined setting.

For still higher temperatures, pyrometer controllers of the radiation type are employed in a similar way.

ELECTRIC WELDING

Two Types of Arc Welding.—Metallic arc welding is a process in which bare or covered wire is used as an electrode for depositing metal in the joint or fracture to be welded, and requires somewhat different electrical conditions from carbon arc welding.

Owing to the array of different types and sizes of equipment now offered by manufacturers when submitting tenders, the engineer, should he lack knowledge of the technical considerations required, may find the choosing of the right kind of plant extremely difficult.

Types of Arc Welding Machines.—Electric arc welding machines are of the following four types: For A.C. or D.C. supplies, motor generator sets possessing drooping or level characteristic generators. For A.C. supply only, static transformer sets, engine-driven sets of the petrol or Diesel types, and lastly, welding generators, arranged for belt drive. All these types can be subdivided into single or multi-operator, portable and stationary equipments.

Where a direct-current supply is available, a motor generator set must be installed, the motor being wound to suit the voltage of the local electric power mains. It is recommended that multiples of single- and/or double-operator sets, comprising dynamos of the drooping voltage type, should be used for the following reasons:

When a number of single- or double-operator plants are in operation, there is no risk of a *total* shut-down of the welding shops in case of breakdown.

Consumption of electric power will be considerably less than that of a multi-operator machine of the level compound-wound type for a given number of welders in each case.

The smaller units, being usually self-contained, can be easily moved to positions most convenient for the work in hand.

There is no possibility of electrical interference between operators (many level characteristic machines give trouble in this respect).

The length of heavy welding cables is reduced to a minimum, as each machine can be placed near the job.

They can be paralleled when required to give larger currents to one welder.

Against the above is the question of initial cost of a number of single- or double-operator sets, but this is offset by lower running costs and the many other advantages enumerated above.

Static transformer sets again have certain advantages and disadvantages.

This type of plant can be obtained at a comparatively low initial cost, and has the advantage of high overall electrical efficiency, and maintenance charges are reduced to a minimum as there are no rotating parts.

Its welding performance is equal to that of a generator giving direct current, and is not recommended for overhead welding, unless special electrodes are used ; bare wire should never be used with a transformer plant.

Engine-driven sets are useful in cases where no mains supply is available.

These may be driven by either a petrol or Diesel engine. For works and isolated situations where no electric power is available, there is naturally no alternative to an engine-driven set.

Plant of this description with a petrol engine has the advantage of lower first cost and total weight, but the Diesel engine-driven plant is now becoming popular owing to its extremely low running cost, and to the fact that they can be relied upon to give good service under almost any conditions.

Most engine-driven sets are required as portable units. Therefore, in order to keep the weight, dimensions and running costs down to a minimum they should be limited to one or two operators.

When necessary, two drooping characteristic dynamos can be built into one frame, in order to conserve space, but it would not be a practicable proposition to have more than two in tandem, and it is for that reason that a portable engine-driven set should never be specified for more than two welders.

With regard to capacity, a single-operator 200-amp. machine will fulfil most requirements for general repair and fabrication work, but when it is desired to provide for two men, the ideal is a double dynamo, as described above, each half having an output of 200 amps., but so arranged that they can be easily and quickly put in parallel to give up to 400 amps. to one man when necessary. In this connection it may be mentioned that a great deal of research work is now being undertaken by electrode manufacturers relative to high-speed

welding by means of special electrodes requiring much larger currents than have been used in the past, and many large engineering concerns have already installed the necessary welding plant to enable them to take advantage of this development and thus speed up production.

Therefore, a double dynamo can be considered most elastic in its uses, as by a touch of a switch it can be instantly converted from a two-operator 200-amp. set into a single-operator 400-amp. machine for high-speed welding.

Welding Accessories.—In addition to the different types of welding plant described above, the following accessories should form a part of every operator's equipment.

One electrode holder, fitted with a length of flexible cable to connect to plant.

One length of flexible cable, for connecting the job to the plant.

One face screen, complete with coloured glasses.

One observer's face screen, with coloured glasses.

One pair of leather gauntlet gloves.

One chipping hammer, to remove slag from weld.

One wire brush, to clean the weld after chipping.

A face screen, or helmet, should be made from fibre or other non-conducting material and should have no screws or rivets that *go right through* the insulating material from which they are made. This is an important feature, as otherwise there is a risk of the operator receiving an unpleasant, if not dangerous, shock in the face should he accidentally touch such pieces of metal with his electrode holder.

Electrodes.—With the ever-increasing demands for the application of electric arc welding to the many various specification metals, both ferrous and non-ferrous, the work of the chemist in the laboratory has been enormously increased to meet those demands, with the result that there are a very large variety of electrodes now to be had, and it is, therefore, becoming more and more the works manager's duty to keep himself in touch with whatever advancement has been made, so that only the best results may be obtained from his plant, and to pass on whatever knowledge he may have gained to those to whom it may matter inside the works.

Electrodes for arc welding can be divided into the following three classes:

(*a*) *Bare Rods of Any Ferrous Metal.*—These hardly need description. Experience shows that there is very little

difference in the composition of the deposited metal traceable to the composition of the electrode.

Oxidation has a maximum effect both in respect to the iron and any constituent which is easily oxidized at high temperatures. The only flux produced is oxide of iron, which has no cleaning effect on the surfaces and does not readily separate from the fused metal. Nickel-plating bare electrodes improves them to some extent by protecting the electrode material prior to fusion.

(b) *Dipped or Light-covered Electrodes.*—These electrodes are dipped in some mixture which, on drying, leaves a thin skin of the solids in the mixture. This thin coating affords some protection against oxidation of the electrode surface, and may be of such composition as to provide some fluxing action. But a coating of this character is insufficient to provide the quantity of flux required for some of the reactions above indicated.

It is necessarily fragile and easily removed by handling. But such dipped electrodes are an improvement on bare electrodes and give sufficiently good results for some jobs.

(c) *Flux-covered Electrodes.*—These electrodes are coated with a material of substantial thickness and solidity calculated to provide protection to the electrode.

Flux-covered electrodes have in general a spiral winding of asbestos yarn as the basis of the covering. Asbestos is a valuable flux in itself, as it fuses and combines with iron oxide into a compound silicate which, being very light and mobile, is easily removed after solidification, leaving a clean surface—an important advantage for work which requires more than one run of welding. Asbestos yarn also makes an excellent vehicle and support for the other constituents of the covering, and with a suitable binder makes a tough-surfaced sheath to the metal core. These electrodes, therefore, travel and handle without loss and damage.

The general result of much experience is that for welding iron and steels, it is useless to adapt the composition of the metal electrode to that of the work. The only way to be sure of getting a weld metal of any desired composition is to adapt the composition of the covering.

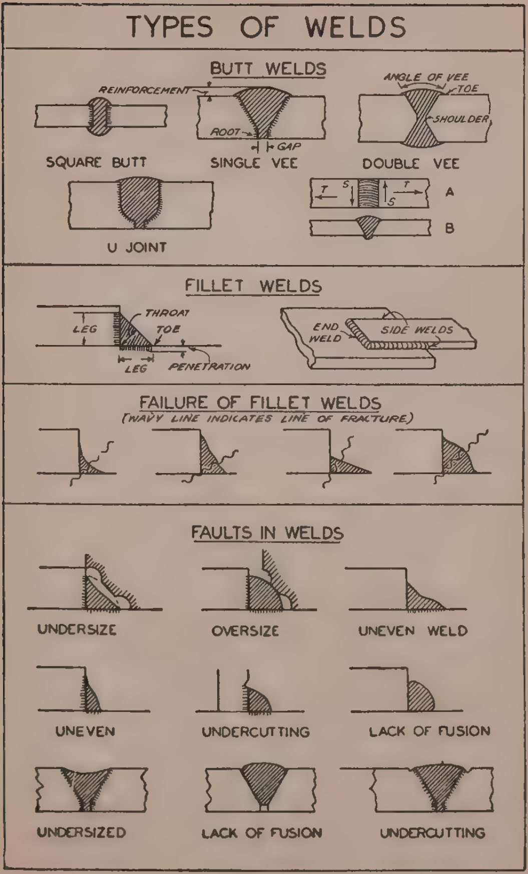
Consequently, the usual practice is to use for the metal of the electrode a standard mild steel and to put upon this standard core a covering which will, by its action as a flux, impart to the weld metal those ingredients which are necessary to make it match the work material.

For example, when welding cast-iron the coating carries

carbon in such a form and quantity as to combine with the metal in the required manner, with the result that a microscopic examination of a section across a weld shows a structure which is that of a typical cast-iron. Similarly with alloy steels, the desired composition is produced by flux reaction with the deposited metal. This practice is convenient and economical.

For electric arc welding, electrodes are manufactured for welding mild steel, high tensile steel, special Admiralty steel, and also for cast-iron, Monel metal, copper, brass and bronze.

Special electrodes are required for welding stainless steel and iron.


TYPES OF WELDS
BUTT WELDS
REINFORCEMENT
ROOT
GAP
ANGLE OF VEE
TOE
SHOULDER
SQUARE BUTT
SINGLE VEE
DOUBLE VEE
T
S
A
B
U JOINT
FILLET WELDS
THROAT
LEG
TOE
LEG
PENETRATION
END WELD
SIDE WELDS
FAILURE OF FILLET WELDS
(WAVY LINE INDICATES LINE OF FRACTURE)
FAULTS IN WELDS
UNDERSIZE
OVERSIZE
UNEVEN WELD
UNEVEN
UNDERCUTTING
LACK OF FUSION
UNDERSIZED
LACK OF FUSION
UNDERCUTTING

"IRONEX" ELECTRODES

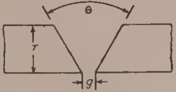
Procedure and Strength of Fillet Welds for Downhand Welding

Size of Fillet.	Throat Thick-ness.	Num-ber of Runs.	Gauge of Elec-trode.	Length of Weld per Elec-trode.	Strength in Tons per Linear Inch of Weld. End Welds. 		Side Welds. 		Feet of Elec-trode per Foot of Weld.	Welding Current.	Power Con-sumption per Foot of Weld.	Welding Time per Foot including Chipping and Changing Elec-trode.
In.	In.	No.	S.W.G.	Gge./in.	Ult. Strength.	Wkg. Stress.	Ult. Strength.	Wkg. Stress.	Ft.	Amps.	Units.	Min.
1/8	0·088	1	12	12/9	2·0	0·5	1·7	0·4	2·0	90	0·1	2
3/16	0·133	1	10	10/9	3·2	0·8	2·7	0·6	2·0	115	0·2	3
1/4	0·176	1	10	10/12	4·0	1·0	3·5	0·9	4·07	115	3	6
		1	10	10/7						115		
		1	8	8/10					1·8	150		3
3/8	0·265	4	10	10/9	6·4	1·6	5·3	1·3	8·0	115	0·7	12
		3	8	8/10					5·4	150		9
1/2	0·354	6	10	10/9	8·4	2·1	7·0	1·8	12·0	115	1·2	19
		5	8	8/10					9·0	150		15
		4	6	6/12					6·0	200		10
5/8	0·441	7	8	8/10	10·4	2·6	8·8	2·2	12·6	150	1·8	21
		6	6	6/12					9·0	200		15
3/4	0·530	10	8	8/10	12·8	3·2	10·8	2·7	18·0	150	2·5	30
		9	6	6/12					13·5	200		23
		8	4	4/15					9·6	240		17
7/8	0·618	13	8	8/10	14·8	3·7	12·4	3·1	23·4	150	3·5	38
		12	6	6/12					18·0	200		30
		11	4	4/15					13·2	240		23
1	0·707	17	8	8/10	16·8	4·2	14·0	3·5	30·6	150	4·4	50
		15	6	6/12					22·5	200		38
		14	4	4/15					16·8	240		30

Note.—Working stresses are to B.S.I. Specification No. 538.

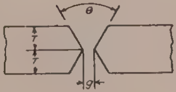
CROSS SECTIONAL AREA OF WELDS

(Welds assumed to be flush)



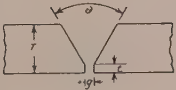
$$\text{AREA} = T^2 \tan\frac{\Theta}{2} + gT$$

$\Theta = 60°$	$T^2 \times \cdot 5774 + gT$
$\Theta = 70°$	$T^2 \times \cdot 7002 + gT$
$\Theta = 80°$	$T^2 \times \cdot 8391 + gT$
$\Theta = 90°$	$T^2 + gT$



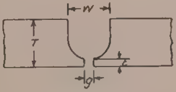
$$\text{AREA} = 2T^2 \tan\frac{\Theta}{2} + 2gT$$

$\Theta = 60°$	$2T^2 \times \cdot 5774 + 2gT$
$\Theta = 70°$	$2T^2 \times \cdot 7002 + 2gT$
$\Theta = 80°$	$2T^2 \times \cdot 8391 + 2gT$
$\Theta = 90°$	$2T^2 + gT$

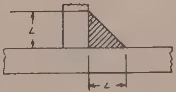


$$\text{AREA} - (T - t)^2 \tan\frac{\Theta}{2} + gT$$

$\Theta = 60°$	$(T-t)^2 \times \cdot 5774 + gT$
$\Theta = 70°$	$(T-t)^2 \times \cdot 7002 + gT$
$\Theta = 80°$	$(T-t)^2 \times \cdot 8391 + gT$
$\Theta = 90°$	$(T-t)^2 + gT$



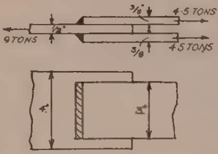
$$\text{AREA} = W\left(T - t - \frac{W}{2}\right) + \frac{\pi W^2}{8} + gt$$



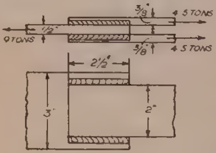
$$\text{AREA} = \tfrac{1}{2} L^2$$

$$\text{AREA} = Tg$$

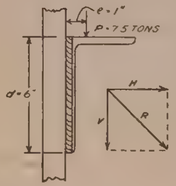
DESIGN OF WELDS



Example 1. Attachment of member by end fillet welds.
Load per flat = 4·5 tons.
Length of weld per flat = 3 in.
Load per inch of weld = $\frac{4·5}{3}$ = 1·5 tons.
Strength of $\frac{3}{8}$-in. end weld = 1·6 tons from tables.*
Hence use $\frac{3}{8}$-in. end welds.



Example 2. Attachment of member by side fillet welds.
Load per flat = 4·5 tons.
Using $\frac{1}{4}$-in. side fillet welds.
Strength = 0·9 tons per lin. in. from tables.
Length of weld required = $\frac{4·5}{0·9}$ = 5 in.
There are two welds per flat.
Hence length of welds are $\frac{5}{2}$ = 2½ in.



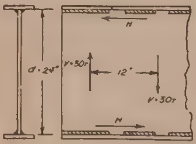
Example 3. Side fillets under combined stress.

$$V = \frac{P}{2d} = \frac{7·5}{2 \times 6} = 0·625 \text{ tons.}$$

$$H = \frac{\frac{Pe}{2}}{\frac{d^2}{6}} = \frac{7·5 \times 1 \times 6}{2 \times 6^2} = 0·625 \text{ tons}$$

$$R = V^2 + H^2$$
$$= 0·625^2 + 0·625^2.$$
$$= 0·78 = 0·88 \text{ tons.}$$

From tables $\frac{1}{4}$-in. side fillet = 0·9 tons.



Example 4. Weld joining flange to web in plate girder.
Vertical shear near end of girder = 30T.
Horizontal shear between web and flange = $\frac{30 \times 12}{24}$ = 15 tons.
From tables $\frac{1}{4}$-in. side fillet weld gives 0·9 tons per in. hence length of $\frac{1}{4}$-in. weld required = $\frac{15}{0·9}$ = 16·7in.
Weld 6 in. miss 3 in. 2 in. (AH) each side would give 18 in. It is usual, however, to weld continuously especially at the compression flange.

*Electrode maker's tables giving strength of various welds.

HOME OFFICE REGULATIONS *RE* ELECTRIC WELDING

It may be as well to summarize for the benefit of the readers of this book the printed memorandum on electric arc welding recently published by the H.M. Stationery Office, on behalf of the Factory Department of the Home Office. The introduction to these regulations states that the process of electric arc welding by hand is being widely adopted in engineering works and repair shops in shipyards, and for constructional and repair work *in situ* on other premises. While the onus of providing for the working of the process in a safe manner rests with the Occupier of the Works, the workman is also responsible for using the safeguards provided in a proper manner.

Precautions required in respect of danger when electric arc welding is being undertaken are from—

1. Electric shock.
2. Radiations from the arc.
3. The scattering of hot particles of globules of metal.
4. Flying pieces of sharp slag when being chipped away after welding.

The Home Office authorities favour the use of direct current, as when direct current is used at the right pressure the danger of a serious electric shock is practically negligible. In view of this, adequate precautions against accidental electric shock have to be taken when using alternating current. A most important precaution concerns the construction of the electrode-holder. This should be provided with a handle of tough non-ignitable insulating material so constructed that the welder cannot touch any live part with the hand with which he holds it.

Special risks mentioned in the memorandum include welding of stagings, boiler work and rail welding.

An interesting section is devoted to protective glass, which should always conform to that specified by the British Standards Institution in their British Standards Specification No. 679—1936, " Protective Glass for Welding and Other Industrial Operations."

MECHANICAL UNITS

Force.—The unit is the pound weight (lb.).

Work.—The work done by a force is the force multiplied by the distance—the unit being the *foot-pound* (ft.-lb.).

Power.—The rate of doing work is the power and is stated in foot-pounds per second or minute.

Horse-Power.—One horse-power (H.P. or h.p.) is equal to 33,000 ft.-lb. per minute or 550 ft.-lb. per second.

Energy.—This is defined as power × time and is therefore stated in horse-power hours (h.p.-hrs.). These are the same units as work, since

$$\text{Energy} = \text{power} \times \text{time} = \frac{\text{ft.-lb.}}{\text{time}} \times \text{time} = \text{ft.-lb.}$$

Torque.—A force acting circumferentially round the periphery of a circle exerts a torque at the centre, i.e. a twisting moment. The value of a torque is the force × the radius at which the force acts. A torque may be in pound-inches (lb.-in.) or pound-feet (lb.-ft.).

Torque and Power.—The relation between torque and power is found from the work done by a torque. For one revolution the work done is the force × the circumference, i.e.

Work done per rev. $= 2\pi r\text{F}$ where Fr or rF is the torque
$= 2\pi\text{T}$ where T = torque.

The horse-power can be obtained from the work done per minute or per second, so that,

$$\text{h.p.} = \frac{2\pi\text{T} \times \text{r.p. min.}}{33{,}000} \text{ or } \frac{2\pi\text{T} \times \text{r.p. sec.}}{550}$$

H.P. and Kilowatts.—One h.p. is equal to 746 watts, so that 1 kilowatt equals $1\frac{1}{3}$ h.p. approximately. For motor calculations the efficiency of the motor must be taken into account.

H.P. and Heat Equivalent.—The units of heat are:
B.Th.U. = heat required to raise 1 lb. of water 1° F.
C.H.U. = heat required to raise 1 lb. of water 1° C.
1 C.H.U. = $\frac{9}{5}$ B.Th.U.

The relation between heat and work is given by

1 B.Th.U. = 778 ft.-lb.

so that 1 kilowatt = 3,440 heat units per hour (B.Th.U.).

Efficiency.—This may be obtained from either

$$\frac{\text{Output}}{\text{Output} + \text{losses}} \text{ or } \frac{\text{Input} - \text{losses}}{\text{Input}}$$

MECHANICAL NOTES

TRANSMISSION OF POWER

SHAFTING is still used for distribution of power to the various machines in a factory, although individual drive has reduced the number of cases where this method is used.

Where shafting is used the drive to the machine is usually by belt or rope drive, the starting or stopping of the machine being controlled either by a clutch or by fast-and-loose pulleys.

Much has been said and written relative to the comparative merits of group and individual drive, and the latter has come into favour to a large extent due to the use of smaller-powered machines for general production work as against the large units used some time ago.

Many engineers still consider that group drive has certain advantages when properly planned. Engineers' shops still use it for driving groups of machines—mainly in those cases where the machine is not supplied with its own motor incorporated in the design. Data taken from actual installations shows that the total power costs are less for group drive for many classes of work.

Small production machines now tend to be self-contained and the machine is designed to include the motor as an integral part of the design. Larger machines, even when driven by their own motors, often have the motor separate and some form of transmission is required from the motor to the machine.

Where the purchaser of the machine has to arrange for the connection of the driving motor there are several ways in which this can be arranged. The flat belt which is generally used for driving from line shafting has the objection that it requires a fairly long drive, and for individual drives it has to a large extent been replaced with the V-belt and the chain drive.

The V-belt drive is a development of the rope drive which has been so satisfactory in driving textile and similar machinery, and has the advantage that the adequacy of the drive is not dependent entirely on the tautness of the belt. There

is thus less tendency for belt-slip to occur, and as a multi-belt drive is used except in the smallest sizes there is the added advantage that the breakage of one of the belts does not immediately shut down the machine. V-belts are now used for transmitting power up to several hundred horse-power and form a large proportion of the belt drives in use to-day.

Chain drives have the special advantages that the drive is positive, there is no possibility of slip, and if properly designed and lubricated no attention or renewals will be required for many years. In some cases the drive is too harsh and some form of shock-absorbing device is necessary to avoid irregular running or shocks to the machine due to unsmooth operating conditions. They take up very little space and there are numerous types suitable for various forms of drive.

Direct drive is to be preferred where it is convenient as regards running speeds (i.e. when the motor speed is suitable for direct connection to the driving shaft of the machine), but here again it may be necessary to include some shock absorber in the form of a flexible clutch.

The comparatively high speeds at which induction motors run for high efficiency and power factor (usually from 700 to 3,000 r.p.m. approx.) often makes it difficult to connect direct to a machine, and on this account gearing is often used. Reduction gears—either worm- or spur-gearing, or a combination of both—are now manufactured to give any desired reduction ratio and can be obtained either as separate units or specially built on to the motor itself. It is thus possible to buy a motor which has a final shaft-speed of any value from 3,000 r.p.m. down to as low as one revolution in 24 hours. Final speeds of from 10 to 500 r.p.m. are quite standard productions.

When considering any form of drive, due note must be taken of starting and stopping arrangements. With individual drive no disconnecting gear is required as a rule, but if it is necessary to have instantaneous stopping some form of disconnection and braking may have to be arranged for.

Further, there is the question of starting up under load. All motors have a limited starting torque, and in the case of induction motors this is not very large. Where the starting torque required is high, some form of clutch will be necessary. This may be hand controlled or automatic, as, for example, the centrifugal-type clutch. This latter has also an advantage that it will operate as an overload device—this being a definite advantage with some types of machinery.

All motor control gear is—or should be—fitted with push-

button stopping, and in all cases where there is no mechanical disconnecting gear arrangements should be made for the "stop" button to be conveniently placed for immediate stopping of the machine by the operator. More than one of these controls may be necessary in order to make sure that it is always to hand wherever the operator may be round the machine.

When considering any form of drive engineers should take advantage of the advice of the manufacturers of power transmission devices. Their accumulated experience enables them to supply a suitable and economical drive and to avoid difficulties of which the works engineer is not aware. This advisory service is always willingly given by manufacturers, who are only too anxious not to have their equipment used incorrectly or under unsuitable conditions.

SHAFTS AND SHAFTING

Shafts for transmitting power may be in simple torsion, as in the case of a direct-coupled motor driving a fan, or they may be under both torsion and bending, as in the case of line shafting with several drives in between bearings.

The stress due to pure torsion in a solid shaft is given by the formula—

$$T = \frac{\pi}{16}.f_s d^3$$

where d = diameter of shaft in inches.
f_s = shear stress in lb. per sq. in.
T = torque in in. lb. units.

The relation between torque and h.p. is given by

$$\text{H.P.} = \frac{2\pi T \times \text{R.P.M.}}{33{,}000} \text{ where T is in ft. lb. units.}$$

Bringing T to in. lb. units and substituting for T

$$\text{H.P.} = \frac{2\pi \times \pi f_s d^3 \times \text{R.P.M.}}{33{,}000 \times 12 \times 16}.$$

$$= \frac{d^3 f_s \times \text{R.P.M.}}{321{,}000}$$

or

$$d = \sqrt[3]{\frac{321{,}000 \times \text{H.P.}}{f_s \times \text{R.P.M.}}}$$

When using above formulæ the value used for f_s must be the safe or *allowable* shear stress and must take into account the required factor of safety.

Practical Calculations.—In order to simplify calculations relative to the size of shafts a simplified formula may be used, viz.—

$$\text{H.P.} = \frac{d^3 \times \text{R.P.M.}}{\text{C}}$$

where C is a constant depending on the condition of the drives and allowing for any bending stresses due to belt drives from pulleys situated between bearings or at the end of an extended shaft, the average values being:

Torsion drives only	50
Line shafts with pulleys	90
Main drives with pulleys	120

Tables.—The accompanying tables show the maximum horse-power which should be transmitted by various size shafts at different speeds and under the three conditions outlined above. Where there is any doubt the next size above should always be chosen.

It will be realized that the power which any shaft can transmit with safety is proportional to (diameter)^3 and also in proportion to its speed. This latter point enables the tables to be used for intermediate or other speeds. For instance, a line shaft 2 inches in diameter will transmit 8·9 h.p. at 100 r.p.m. The h.p. for 500 r.p.m. will be 44·5 and at 10 r.p.m. 0·89.

Hollow Shafting.—Where it is desirable to save weight, hollow shafting is used, since weight for weight it will safely transmit a greater load.

H.P. OF TORSION SHAFTS (NO PULLEYS)

Dia. in Inches.	R.P.M. of Shaft.								
	100	125	150	175	200	250	300	350	400
1	2·0	2·5	3·0	3·5	4·0	5·0	6·0	7·0	8·0
$1\frac{1}{4}$	3·9	4·9	5·9	6·9	7·8	9·8	11·7	13·7	15·7
$1\frac{1}{2}$	6·7	8·4	10·1	11·8	13·5	16·8	20·1	23·7	27·0
$1\frac{3}{4}$	10·7	13·7	16	18·7	21·4	26·7	32	37·1	42·7
2	16	20	24·0	28	32	40	48	56	64
$2\frac{1}{4}$	22·7	28·5	34·2	40	45·5	57	68	80	91·5
$2\frac{1}{2}$	31·2	39	46·7	54·7	62·5	78	94	109	125
$2\frac{3}{4}$	41·5	51·7	62·0	72·5	83	107	124	144	166
3	54·0	67·7	81	95	108	135	162	189	216
$3\frac{1}{2}$	85·5	107	128	150	171	214	256	300	342
4	128	160	192	224	256	320	384	448	512

H.P. OF SHAFTS FOR LINE SHAFTS

Dia. in Inches.	R.P.M. of Shaft.								
	100	125	150	175	200	250	300	350	400
1	1·1	1·39	1·68	1·95	2·22	2·78	3·34	3·9	4·45
1¼	2·15	2·72	3·22	3·75	4·34	5·4	6·57	7·5	8·6
1½	3·75	4·69	5·61	6·56	7·5	9·37	11·2	13·1	14
1¾	5·95	7·45	8·9	10·4	11·9	14·9	17·8	20·8	23·8
2	8·9	11·1	13·3	15·6	17·8	22·2	26·7	31	35·6
2¼	12·7	15·8	19	22·2	25·4	31·8	38·1	44·4	50·7
2½	17·4	21·7	26	30·2	34·8	43·5	52	60·7	69·5
2¾	23·1	28·8	34·5	40	46	57·5	69	80	92
3	30	37·5	45	52·5	60	75	90	105	120
3½	47·5	59·5	71	83·3	95	119	142	167	190
4	77	89	106	124	142	178	214	249	284

H.P. OF MAIN SHAFTS WITH PULLEYS OR GEARING

Dia. in Inches.	R.P.M. of Shaft.								
	50	75	100	150	200	250	300	350	400
1	0·4	0·6	0·8	1·2	1·6	2·0	2·4	2·8	3·2
1¼	0·78	1·17	1·56	2·32	3·1	3·9	4·6	5·4	6·2
1½	1·34	2·0	2·69	4·0	5·4	6·7	8·2	9·4	10·7
1¾	2·0	3·2	4·2	6·4	8·5	10·7	12·8	15	17·2
2	3·2	4·8	6·4	10·4	12·8	15·9	19·2	22	25·6
2¼	4·5	6·8	9·2	13·7	18·2	22·8	27·2	32	36·2
2½	6·2	9·4	12·5	18·7	25	31·2	37·5	44	50
2¾	8·3	12·4	16·6	25	33	41·5	50	58	66
3	10·8	16·2	21·6	32·4	43	54	65	75	86
3½	17·2	25·6	34·2	51	68	85	102	120	136
4	26·6	38·2	51	77	105	128	153	179	205
4½	36·5	54·5	73	109	146	185	218	255	292
5	50	75	100	150	200	250	300	350	400

FLAT BELT DRIVES

FLAT belts have been used for driving machinery since the earliest days of engineering and are still used for general work. They are essentially simple to install and have the great advantage that they can be used on fast-and-loose pulleys for starting and stopping operations.

The various types of belting in general use are the following:

Leather Belting.—Perhaps the first type of flat belt. Both tanned and rawhide belts are used. For ordinary use oak-tanned leather is used, whereas chrome-tanned leather is generally chosen for extremely severe conditions. The latter will withstand wet and varying temperatures and is suitable for high-speed running over small pulleys.

Laminated leather belts made up of strips laid side by side have proved most satisfactory and can be used for the heaviest duties.

Cotton Belting.—Belting woven from cotton may be used under what may be termed ideal conditions. It will not withstand acids, fumes, damp or wet, but is not affected by oil. Used in clean industries such as food and textile. Cheap in first cost.

Hair Belting.—Belts woven from camel or goat hair are superior to cotton and will withstand acids and bad conditions quite satisfactorily. They are suitable for tropical situations and for driving machines with shock loads.

Balata Belting.—Cotton belts impregnated with balata (a gum obtained from Jamaica and other places) form an ideal drive for general use. The balata, which is also laid between the plies forming the belt, protects the belt from the weather and also strengthens it, preventing stretch, and gives it a long life even in the presence of dust and grit. It is competitive in price and holds fasteners well.

Rubber Belting.—The use of rubber for impregnating and covering cotton belts has developed rapidly since its introduction some years ago. It will withstand practically all con-

H.P. FOR SINGLE LEATHER BELTS

Speed in Feet per Min.	Width of Belt (Inches).					
	2	4	6	8	10	12
200	0·6	1·2	1·8	2·4	3·0	3·6
300	0·9	1·8	2·7	3·6	4·5	5·4
400	1·2	2·4	3·7	4·9	6·1	7·3
500	1·5	3·0	4·6	6·1	7·6	9·1
600	1·8	3·6	5·4	7·3	9·1	10·9
800	2·4	4·8	7·2	9·6	12·1	14·5
1,000	3·0	6·0	9·0	12·0	15·1	18·1
1,500	4·5	9·0	13·6	18·1	22·7	27·2
2,000	6·0	12·1	18·1	24·2	30·3	36·3
2,500	7·5	15·1	22·7	30·3	37·9	45·4
3,000	9·0	18·0	27·0	36·0	45·0	54·0
4,000	10·1	20·3	30·5	40·7	50·9	61·0
5,000	15	30	45	60	75	90

Other belt speeds and widths can be taken as proportional.

ditions of weather and fumes and is therefore much used for outside work. The main disadvantages are that it may be damaged mechanically if not properly handled and is affected by oil. It forms an exceedingly reliable drive when correctly installed and will wear for a long time.

Belt Dressings.—There are many good dressings on the market which, when correctly applied, increase the friction between the belt and the pulley, but care should be taken that the dressing is suitable for the type of belt and that too much is not applied. A good dressing will enable many belts to run slacker than without dressing, and the belt will last longer, but if too much dressing is applied the surface becomes lumpy and the dressing attracts dust and grit—always detrimental to a belt.

Leather and balata belts should be dressed sparingly but regularly with a dressing which is not tacky or resinous. If too much has been applied it can generally be removed by washing with petrol or turpentine or a mixture of the two. Rubber belts should not normally be dressed at all, as if run at the correct tautness they will grip satisfactorily. A very small quantity of castor or boiled linseed oil will remove the bloom and improve the drive when new. Rubber and balata belts should be washed with soap and water only, as spirits will ruin the belt.

HORSE-POWER TRANSMITTED

The power transmitted by a belt depends on the effective tension in the belt and the speed at which it runs. The effective tension is the difference between the "pull" on the tight and slack sides of the belt. In a properly designed belt drive the stress in the belt along its slack portion should not be very high. If there is considerable initial stress in the belt when not running the belt is too short or has been tightened to prevent slip, which should be remedied in some other way. This may mean that the belt is too small for its work or that it is in bad condition.

The power transmitted by a belt is given by

$$\text{H.P.} = \frac{(T_1 - T_2) \times \text{Velocity of belt}}{33{,}000},$$

the velocity being in feet per minute. The effective tension is given by $(T_1 - T_2)$, being the tensions in the taut and slack side, respectively. As T_1 is the highest load on the

H.P. FOR BALATA BELTS PER INCH WIDTH

Speed in Feet per Min.	Thickness of Belt.					
	3-ply.	4-ply.	5-ply.	6-ply.	7-ply.	8-ply.
500	0·6	0·8	1·0	1·2	1·4	1·6
1,000	1·2	1·6	2·0	2·5	2·9	3·3
1,500	1·8	2·5	3·1	3·7	4·3	5·0
2,000	2·5	3·3	4·1	5·0	5·8	6·6
2,500	3·1	4·1	5·2	6·2	7·2	8·3
3,000	3·7	5·0	6·2	7·5	8·7	10·0
3,500	4·3	5·8	7·2	8·7	10·2	11·6
4,000	5·0	6·6	8·3	10·2	11·6	13·3
5,000	6·2	8·3	10·4	12·5	14·5	16·6

Intermediate speeds can be taken as proportional.

belt the maximum power which can be safely transmitted is fixed by this value. The maximum safe value of T_1 can be fixed according to the type of belt, its width and thickness and the general conditions under which it runs.

This maximum safe tension may be either fixed by limiting the stress per square inch of cross-section or per inch wide per layer or per ply. Average figures are as follows:

Leather 5 mm. thick	50 lb. per inch width
Balata . . .	12–16 lb. per inch width per ply

Arc of Contact.—In all belt drives it is important to obtain as large an arc of contact as possible, and on this account pulleys with large difference in diameters should be avoided when possible. In cases where one pulley is much smaller than the other an allowance must be made for the reduced arc of contact on the small pulley and a wider belt used.

Danger of Overloading.—Most of the troubles occurring with belt drives are due to overloading or incorrect fitting. When deciding on the size of a belt allowance must be made for any irregularities in the power transmitted—the belt must be able to deal with the maximum power, not the average. It must also be remembered that the belt-fastener (if it is not endless) will reduce the efficiency and also that the condition of the belt is not always good. It is in general economical to install too large a belt, provided this is not carried to excess.

Ordering Belts.—When ordering belts the information usually required by the makers includes: sizes of pulleys, speeds of pulleys, pulley centres, H.P., details of load as regards shock and conditions under which the belt will work. It is also advisable to state the type of pulley to be used and whether the belt will work on fast-and-loose pulleys.

PULLEYS

PULLEYS for use with flat belts are usually one of four types —wood, cast-iron, wrought-iron, or pressed-steel. They may be either solid or split. These terms refer essentially to whether they are divided or not so that they can be fitted to existing shafts between two bearings.

Wood Pulleys.—Although ideal from the point of view of gripping the belt, wood pulleys have not proved very popular in this country. They are cheap and light in weight and tend to absorb shocks where the load is uneven. In America, where suitable woods are available, they are used to a greater extent and give long service.

Wood pulleys are usually made in halves, i.e. split, and are arranged for a "grip" fit on the shaft. Varying sizes of shafts are allowed for by means of bushes, and in this way the number of pulleys which need be stocked is reduced to a minimum. They must, however, not be used in damp situations on account of losing their shape.

Cast-iron Pulleys.—Cast-iron pulleys are made both solid and split, but in this case a large proportion are solid as the cost of making a cast-iron split pulley is much higher than for the solid type. This is due to the necessity of fitting the two halves accurately. The pulleys should be turned on the face and edges and curved arms or spokes are to be preferred as they avoid inherent stresses due to cooling in the mould. Cast-iron pulleys are invariably keyed to the shaft.

Wrought-iron Pulleys.—These pulleys are really made of steel but are referred to as wrought-iron as this was the material originally used for this form of pulley. The rim is rolled sheet and the spokes of round mild-steel. Owing to the method of construction these pulleys are easily made "split," although they are also made solid. The hubs are cast-iron or steel, according to the severity of the duty for which the pulley is intended.

Pressed-steel Pulleys. This form is a development of the wrought-iron pulley and uses sheet construction throughout instead of riveted spokes. Here, again, they are usually split and may be fixed to the shaft either by gripping bushes or by a key. They are popular for small and medium sizes and in common with wrought-iron they are unbreakable, this being one of the disadvantages of cast-iron pulleys.

Pulley Faces.—Various types of rims are used for pulleys. All these types are available with cast-iron pulleys and most in wood, but wrought-iron and steel pulleys are generally simple flat or crowned faces.

Fast-and-loose Pulleys.—For this type the loose pulley is usually slightly smaller in diameter than the fixed pulley to remove any tension from the belt when running free. Loose pulleys should be bushed with brass or white-metal or fitted with ball or roller bearings to reduce friction losses.

V-BELT DRIVES

One of the first applications of the V-belt was the motor cycle, which employed a rubber belt running in taper grooves. Although it has been superseded by the roller chain for this particular duty, it has been developed to a great extent during the last ten years for general industrial use.

An important reason for its adoption has been the need for shorter and larger ratio drives. With the flat belt a minimum distance between centres is essential, and if the drive ratio is too high, slip difficulties are experienced with the small pulley.

With the V-belt the " grip " is not dependent on the tautness of the belt or belts (although too much slack is not desirable) and extremely short centres and small pulleys can be used.

Modern V-belts are made in rubber and balata types, together with leather for certain purposes. Normally, several belts are used except in the smallest powers, and this has the advantage that the failure of one belt does not immediately put the machine out of action.

Where possible, V-belts should be endless as belt-fastener trouble is then eliminated and any required length can be obtained in the endless form. Correct alignment is essential and oil or spirit must not be allowed to come into contact with the belts.

ROPE DRIVES

Ropes have been used for transmitting power for over a hundred years and the V-belt is a development of this system. When large factories were driven by one large steam-engine, rope drives were used to distribute the power to the different machines in the factory.

Small powers are transmitted by single ropes, but heavy drives consist of several ropes on one pulley. The design of the grooves in the pulleys is a matter of importance, the design differing in various countries.

Ropes are satisfactory for long centre drives. For best results the rope should have the slack side at the top in order to obtain the maximum arc of contact.

The permissible velocity of ropes is much higher than with belts and speeds up to 7,000 ft. per minute are allowable. Angle drives can be used without trouble and several shafts can be driven by one rope, this being one of the reasons for its adoption for textile machinery.

Care must be taken to keep the ropes clean and dry, and special dressings can be obtained to keep the rope in good condition. Water should not be allowed to come into contact with the ropes.

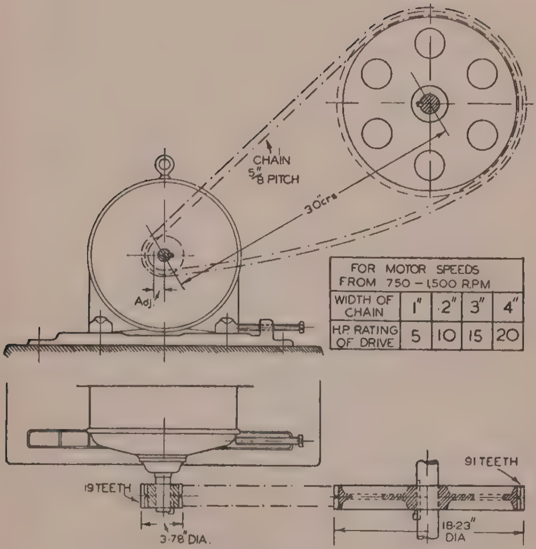
CHAIN DRIVES

Chains used for general industrial drives are of two main types—roller and inverted-tooth. Although both types give similarly good service, the inverted-tooth chain is quieter running at high speeds, although the roller type can actually run at a higher speed. For low speeds the roller type is generally adopted owing to its lower cost and smaller dimensions.

They possess many advantages, especially for slow-speed short-centre drives—the drive is positive—and under proper conditions the life is exceptionally long. Where a definite degree of flexibility or shock absorption is required spring or cush drive devices are available. Where possible, chain drives should be run in an enclosed oil-bath, although open drives even in seemingly unfavourable circumstances have a fairly long life. Dust and grit are the main troubles, but are minimized by proper lubrication, which is essential for all chain drives.

Chain drives are designed according to the actual duty for which they are intended, so that chains used for operating the camshafts of internal-combustion engines vary in character from those used for general industrial use.

Power Transmitted.—As the maximum load which must be used on a chain is a fixed amount, the power which can be transmitted depends on the speed at which it runs and the



FOR MOTOR SPEEDS FROM 750 – 1,500 R.P.M.				
WIDTH OF CHAIN	1"	2"	3"	4"
H.P. RATING OF DRIVE	5	10	15	20

Typical Chain Drive with Approx. Power

details of the drive. Modification must be made for uneven torque, high chain-speed, exceptionally long or short centres, undesirable conditions.

The chain-speed affects the type of chain chosen and there are three groups—heavy, medium, and lightweight chains, with the following speeds :

	Low Speed.	Medium Speed.	High Speed.
Light chains . .	1,250	2,500	3,500
Medium chains . .	800	2,000	2,500
Heavy chains . .	500	1,500	Not made.

Speeds are in feet per minute.

As there is no counter pull in the slack section the H.P. of a chain is given by

$$\text{H.P.} = \frac{\text{L.V.}}{33{,}000}$$

where L is the safe working load in pounds and V the speed in feet per minute. This relationship holds good only for relatively low speeds, and for speeds which are high for the class of chain reduce the horse-power which should be transmitted by a given chain.

Chain wheels should be limited for satisfactory use to 19 teeth for the pinion and 150 teeth for the wheel—this gives a ratio of about 8 to 1, which is the maximum which should be used for general industrial drives.

There is an ideal centres measurement for each class of chain. For nearly equal ratios extremely short centres are satisfactory, but as the ratio increases the centres must be greater to give meshing over a larger arc. This arc should not be less than 90°, and 120° should be aimed at. Long chains give a longer life than short ones and give a certain amount of flexibility. Average drives should not have centres above 10 to 15 feet, a rough guide being that the distance between centres should be between 30 and 50 times the pitch of the chain.

Longer drives of roller chains are permissible for steady drives, and for this type of drive centres of over 30 feet are satisfactory where there are no load variations or shocks. For long centres it is an advantage if the drive can be arranged at an angle of 40° to 60° to the horizontal, or for slow-speed drives a running track can be used to support the chain—adequate lubrication being of course necessary.

The maintenance of chain drives is mainly a matter of

lubrication and adjustment. Enclosed drives need only the proper feeding (automatic or otherwise) with lubricant, but exposed chains must be taken off periodically and cleaned. This is usually effected by washing in a paraffin bath, after which the chain should be well soaked in oil to ensure the paraffin being replaced with lubricant before it is replaced in position.

The tension adjustment (where fitted) must be altered from time to time to take up the stretch of the chain. Usually a certain amount of slack is essential except for very irregular loads. A too tight chain soon wears out. Undue wear may be due to this cause or to incorrect alignment of the wheels—this latter is a very important point.

COUPLINGS

Couplings for connecting lengths of line-shafting, etc., have reached such a stage of perfection that very little need be said. Solid couplings should always be of the recessed or spigot and socket type—the male half generally being the driving portion. Further, all bolt-heads and nuts should be in recesses or protected by a flange.

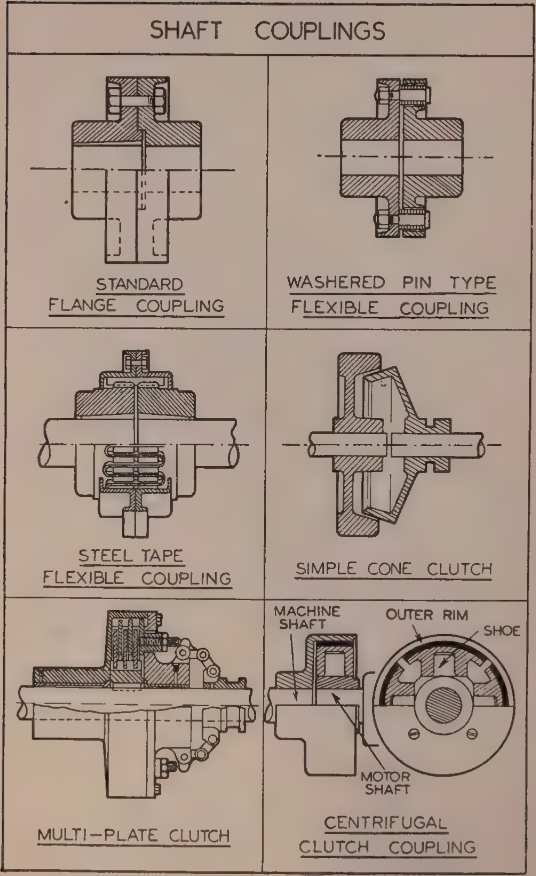
Standard flange couplings can now be bought from stock for all likely sizes.

Flexible Couplings.—The use of flexible couplings has resulted in many types being developed—all or most of them having proved satisfactory.

The simplest form is that of the leather or fabric disc which is used for low horse-power and which also forms a universal joint. All flexible couplings allow for slight irregularities in alignment or end play in addition to smoothing out shocks.

Other satisfactory types include the use of leather washers in the drive-hole, steel tapes interlaced round the periphery of the flanges, and various rubber bush arrangements.

In addition to correct fitting it is important to inspect couplings periodically to make sure that bolts or keys have not become loose. Continual use with loose bolts will eventually damage a coupling beyond repair.


SHAFT COUPLINGS
STANDARD
FLANGE COUPLING
WASHERED PIN TYPE
FLEXIBLE COUPLING
STEEL TAPE
FLEXIBLE COUPLING
SIMPLE CONE CLUTCH
MULTI-PLATE CLUTCH
MACHINE
SHAFT
OUTER RIM
SHOE
MOTOR
SHAFT
CENTRIFUGAL
CLUTCH COUPLING

CLUTCHES

In addition to the widely used fast-and-loose pulley arrangement for disconnecting the load from the drive, there are several types of clutch which enable this to be done by moving a lever or turning a handwheel.

Where it is only required to disconnect when not running, a claw or dog clutch is sufficient, but generally a friction-type clutch is necessary.

Friction clutches may be of the cone, flat plate or rim type, and the contact is either metal to metal or by means of friction material similar to brake-lining. For continual use the friction-lined type gives smoother working, but the lining requires renewing, although usually at infrequent intervals. Several types are shown in the accompanying diagrams.

Centrifugal Clutches.—These are of importance to the electrical engineer as they enable induction and other motors to be started up unloaded and the load will be taken up automatically as the speed increases. They also have the advantage that many of them will " slip " if the load exceeds a certain value and thus prevent a motor from being overloaded. This may avoid the control gear operating and shutting down the plant on a momentary overload.

Centrifugal clutches are of two types—loaded and unloaded. In the unloaded type the shoes are free to grip the rim due to the centrifugal force, whereas in the loaded type they are controlled by a spring which can be adjusted to give the correct working. In the unloaded type adjustment is obtained by altering the weight of the shoes, but this is not so convenient and the adjustment is coarser.

These automatic clutches often allow a standard squirrel-cage motor to be used where otherwise a wound-rotor machine would be required, involving more expense.

Centrifugal safety couplings (for protecting against overload only) are also manufactured for this duty and tend to replace the older strap-type safety devices.

When these clutches are used for lightening the starting load of motors, it is usual to allow the motor to attain a speed of about 75 per cent. full speed before the clutch engages.

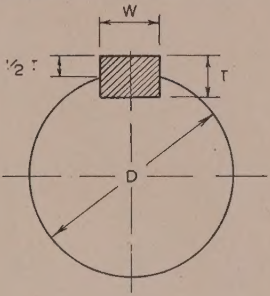
There is every indication that these transmission devices will be much more widely used in the future as their advantages are borne out in actual practice. The " smoothing "

action results in longer life and less maintenance in the transmission equipment and the machinery which is being driven.

Magnetic Clutches.—The use of electro-magnetic pull for transmitting power enables a simple and instantaneous control to be obtained with multiple control at as many points as required.

Magnetic clutches generally use the same friction or gripping system as for mechanically operated models, but the closing or opening is controlled by a solenoid. The electrical system can be designed to give either rapid or slow engagement and a very sensitive control can be obtained where this is desirable. Alternatively, instantaneous operation " in " or " out " can also be obtained.

RECTANGULAR KEYS



SIZES OF RECTANGULAR KEYS

Dia. of Shaft. Inches.	Key Width.	Key Thickness.	
1	$\frac{1}{4}$	$\frac{3}{16}$	Intermediate sizes use Keys of size above, e.g. a $1\frac{1}{8}''$ shaft would have a $\frac{5}{16}'' \times \frac{7}{32}''$ key.
$1\frac{1}{4}$	$\frac{5}{16}$	$\frac{7}{32}$	
$1\frac{1}{2}$	$\frac{3}{8}$	$\frac{1}{4}$	
$1\frac{3}{4}$	$\frac{7}{16}$	$\frac{9}{32}$	
2	$\frac{1}{2}$	$\frac{11}{32}$	
$2\frac{1}{2}$	$\frac{5}{8}$	$\frac{13}{32}$	
3	$\frac{3}{4}$	$\frac{1}{2}$	
$3\frac{1}{2}$	$\frac{7}{8}$	$\frac{5}{8}$	
4	1	$\frac{11}{16}$	
$4\frac{1}{2}$	$1\frac{1}{8}$	$\frac{3}{4}$	
5	$1\frac{1}{4}$	$\frac{13}{16}$	

Normal taper is 1 in 100.

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